NeoBiota 85: 43–79 (2023)
doi: 10.3897/neobiota.85.98902
https://neobiota.pensoft.net

REVIEW ARTICLE

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

# The rise of the Functional Response in invasion science: a systematic review

Larissa Faria[1], Ross N. Cuthbert[2], James W. E. Dickey[3,4,5,6], Jonathan M. Jeschke[3,4,5], Anthony Ricciardi[7], Jaimie T. A. Dick[2], Jean R. S. Vitule[1]

**1** *Laboratório de Ecologia e Conservação, Departamento de Engenharia Ambiental, Universidade Federal do Paraná, Curitiba, Brazil* **2** *Institute for Global Food Security, School of Biological Sciences, Queen's University Belfast, Belfast, Northern Ireland, UK* **3** *Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany* **4** *Freie Universität Berlin, Institute of Biology, Berlin, Germany* **5** *Berlin-Brandenburg Institute of Advanced Biodiversity Research, Berlin, Germany* **6** *GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Kiel, Germany* **7** *Redpath Museum, McGill University, Montreal, Canada*

Corresponding author: Larissa Faria (larissa.faria@fulbrightmail.org)

Academic editor: Sven Bacher | Received 16 December 2022 | Accepted 12 April 2023 | Published 9 June 2023

**Citation:** Faria L, Cuthbert RN, Dickey JWE, Jeschke JM, Ricciardi A, Dick JTA, Vitule JRS (2023) The rise of the Functional Response in invasion science: a systematic review. NeoBiota 85: 43–79. https://doi.org/10.3897/neobiota.85.98902

## Abstract

Predicting which non-native species will negatively impact biodiversity is a longstanding research priority. The Functional Response (FR; resource use in relation to availability) is a classical ecological concept that has been increasingly applied to quantify, assess and compare ecological impacts of non-native species. Despite this recent growth, an overview of applications and knowledge gaps across relevant contexts is currently lacking. We conducted a systematic review using a combination of terms regarding FR and invasion science to synthesise scientific studies that apply the FR approach in the field and to suggest new areas where it could have valuable applications. Trends of publications using FR in invasion science and publications about FR in general were compared through the Activity Index. Data were extracted from papers to reveal temporal, bibliographic, and geographic trends, patterns in study attributes such as type of interaction and habitat investigated, taxonomic groups used, and context-dependencies assessed. In total, 120 papers were included in the review. We identified substantial unevenness in the reporting of FRs in invasion science, despite a rapidly growing number of studies. To date, research has been geographically skewed towards North America and Europe, as well as towards predator-prey interactions in freshwater habitats. Most studies have focused on a few species of invertebrates and fishes. Species origin, life stage, environmental temperature and habitat complexity were the most frequently considered context-dependencies. We conclude that while the FR approach has thus far been narrowly applied, it has broad potential application in invasion science and can be used to test major hypotheses in this research field.

Copyright *Larissa Faria et al.* This is an open access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

**Keywords**
ecological impact prediction, hypothesis testing, invasive alien species, resource use, risk assessment, trophic interactions

## Introduction

With rates and effects of biological invasions magnifying worldwide (Pyšek et al. 2020; Diagne et al. 2021; Seebens et al. 2021), predicting and quantifying which non-native species (NNS) will have the greatest impacts has become a research priority, especially in the face of ongoing anthropogenic environmental change (Kumschick et al. 2015; Ricciardi et al. 2021). Invasion science has been slow to develop predictive approaches that explain and forecast the negative ecological impacts of existing invasive and emerging NNS under relevant contexts (Dick et al. 2017a). This hampers management prioritisation towards the most damaging species across invasion stages (Robertson et al. 2020). Moreover, research has been highly uneven across taxa, trophic groups, regions and forms of impact (Pyšek et al. 2008; Bellard and Jeschke 2016; Braga et al. 2017; Crystal-Ornelas and Lockwood 2020), possibly reflecting the lack of standardised and broadly applicable methods (but see Dick et al. 2014, 2017a).

The rapid exploitation of resources (e.g. food, water, space, nutrients) is considered a characteristic trait of high-impact invasive consumers (Johnson et al. 2008; Morrison and Hay 2011; Ricciardi et al. 2013). It has been hypothesized that the most ecologically disruptive NNS typically exploit resources more efficiently than other resident species (Funk and Vitousek 2007; Ricciardi et al. 2013). On this basis, a valuable and still largely underexploited approach to quantify and compare NNS ecological impact is the classical Functional Response (*sensu* Solomon 1949; Holling 1959), the relationship between resource availability and resource consumption rate. In addition to being employed in studying predator-prey dynamics (e.g. Sinclair et al. 1990; Eby et al. 1995; Heikinheimo 2001), the Functional Response (FR) has also been used to evaluate the efficacy of biological control agents towards target organisms (van Driesche and Bellows 1996; Madadi et al. 2011), sport fish-angler interactions (Johnson and Carpenter 1994; Yodzis 1994; Eggleston et al. 2003), and impacts of human hunting on wildlife conservation (Sinclair et al. 1998; Swanepoel et al. 2015). Over the past decade, the FR has been applied to predict and quantify NNS impacts on native populations and communities (Dick et al. 2014, 2017a).

The Functional Response has been broadly characterised into linear (Type I), hyperbolic (Type II), sigmoidal (Type III), or dome-shaped (sometimes called Type IV) curves (Jeschke et al. 2004). As many invasion hypotheses are centred on trophic interactions (Catford et al. 2009; Ricciardi et al. 2013; Enders et al. 2020), FRs can be useful in hypothesis testing and measuring trophic impacts of non-native consumers (Dick et al. 2014). Indeed, as all living organisms use resources, there is no limit taxonomically or trophically to the use of FRs, and hence it could be a unifying method across all NNS (Dick et al. 2017a). Furthermore, the type of FR mediates impact;

for example, predators exhibiting Type II FRs are deemed to be more destabilising to resource populations than those exhibiting Type III FRs, owing to high proportional feeding rates at low resource densities and a concomitant lack of low-density refugia for prey (Murdoch and Oaten 1975).

The comparative FR approach has been grounded in relative pairwise comparisons of native and NNS under standardised conditions, or by comparison of the same NNS under different contexts when trophic analogues are absent, normally in controlled laboratory environments (but see Smout et al. 2013; Goss-Custard et al. 2006 for field-derived FRs). By carefully matching comparator species according to size, sex, life stage, and other variables, a balanced comparison of *per capita* impacts is sought, usually in terms of consumer attack rates, handling times, maximum feeding rates, and combinations of such parameters (Cuthbert et al. 2019b), acknowledging NNS impacts relative to native consumers or different contexts. Critically, NNS with a higher magnitude FR, characterised by greater search efficiencies and/or shorter handling times (depending on the FR shape), are predicted to have greater *per capita* ecological impacts than trophically analogous native species with lower magnitude FRs (Fig. 1). Across studies, there is a tight corroboration of these experimentally derived patterns with actual impacts recorded in the field (Dick et al. 2017a). Indeed, the FR could be considered a universal *per capita* measure for consumptive effects within the classical Parker-Lonsdale impact equation which defines that the total impact of a given NNS is the product of its abundance, range, and *per capita* effect (Parker et al. 1999; Dickey et al. 2020).

A species FR is not a fixed trait and, like NNS impacts, can vary across myriad biotic and abiotic contexts. The advantage of FRs is that these context-dependencies can be incorporated into experimental designs to provide more realistic assessments while isolating the variables of interest (Dick et al. 2017a, 2017b; Penk et al. 2017), and help to understand how NNS impacts relate to physical habitat conditions (i.e. the Environmental Matching Hypothesis; Iacarella et al. 2015a). Nevertheless, although context-dependent variation remains a challenge for reliably predicting NNS impacts, the malleability of the FR approach makes it an excellent tool to explicitly incorporate and test context-dependencies. Given ongoing climate and land-use changes, for example, it is relevant to test variation in FRs under different temperatures (Englund et al. 2011; Uiterwaal and DeLong 2020) or related abiotic variables to understand how impacts of NNS may be altered. Furthermore, FRs can be combined with different levels of habitat complexity, a feature that may have direct implications on the type of FR and thus on resource population stability (Toscano and Griffen 2013; Murray et al. 2016; Kalinkat et al. 2023). Biotic contexts, such as organism life stage, multiple predator effects or higher-order predator presence, can also be useful to understand impacts, considering that consumers may not forage alone in nature (Smout et al. 2010; Ball et al. 2015; Médoc and Spataro 2015).

The FR measures individual *per capita* effects and then can be scaled with the numbers of individual consumers to derive a measure of overall impact (i.e. Total Response = Functional Response × Numerical Response; Holling 1959), as has been done with biological control (e.g. killing rate *per* individual agent × number of agents)

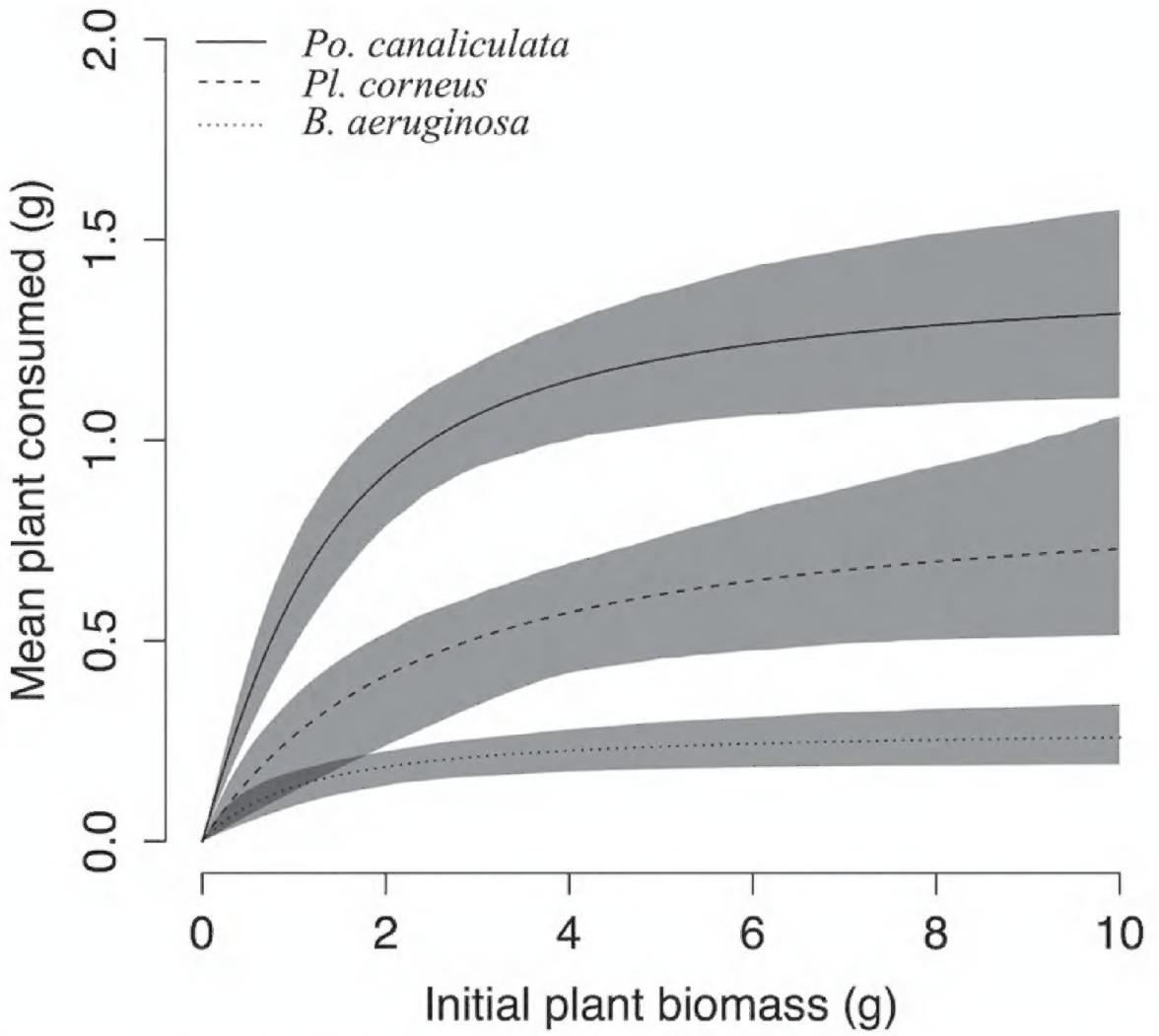


**Figure 1.** Functional Responses of known impactful invasive non-native species (NNS) are often higher when compared to those of native or non-invasive NNS trophic analogues, as shown for aquatic snails: the invasive NNS *Pomacea canaliculata*, the non-invasive NNS *Planorbarius corneus*, and the native *Bellamya aeruginosa* feeding on four locally occurring plant species in China. Reproduced from Xu et al. (2016).

and fisheries assessments (e.g. overall offtake rates by predators). The Relative Impact Potential (RIP) metric integrates numerical responses (consumer population change) or their proxies – such as field abundances or other population-level metrics (Dick et al. 2017b; Dickey et al. 2020) – to reveal overall expected field impacts of novel NNS. Further advances to this approach have amalgamated different parameters of the FR to streamline impact comparisons (e.g. the Functional Response Ratio, FRR; Cuthbert et al. 2019a) and integrated measures of propagule pressure that combine impact with risk assessment (Dickey et al. 2022). Moreover, GIRAE (Generalised Impact = Range size × Abundance × *per*-unit Effect) has been recently developed as a tool to predict *per capita* ecological and economic effects of NNS based on available data, again stemming from the Parker-Lonsdale impact equation (Latombe et al. 2022).

There are some important criticisms to the comparative FR approach related to its generalization and the potentially unrealistic nature of the experiments. Vonesh et al. (2017) argues that if consumers used in trials have different ecological parameters beyond those estimated in experiments, the comparison of their FRs has less ecological meaning. Specifically, two consumers may differ in their mortality rate when resources are absent (background mortality) and also on the proportion of resource consumed

that is effectively converted into increasing the abundance of the consumer (conversion efficiency), which can substantially influence consumer effects on resource dynamics in the long-term (Landi et al. 2022). Likewise, Griffen (2021) points out that the comparative FR approach is only useful if species respond similarly to the artificial conditions and techniques employed, and that directly scaling FRs measured on individuals to entire populations could yield misleading results. However, previous syntheses of the limited number of FRs available in the context of invasion impacts attest to its high potential to explain and predict impact (Dick et al. 2017b).

Despite the rapidly increasing use of the FR approach in invasion science, we still lack a synthesis of its application in this field that could reveal knowledge gaps to be addressed and avenues for future improvement. Currently, studies are potentially disparate across different life stages of the same organism, taxonomic groups, trophic groups, environments, and geographic regions, meaning likely unevenness in the testing of the approach in different study systems, and in turn frustrating the holistic assessment of its efficacy. Therefore, this timely systematic review of studies to date aims to synthesise the available scientific literature that applies the FR approach in invasion science to elucidate potential shortcomings that can be addressed in future work to improve the representativeness and the explanatory and predictive capacities of the method.

## Methods

### Literature search and screening

We performed a literature search in January 2021 using the Web of Science database (WoS). The following combination of search terms was used: TOPIC = ("functional response*") AND (invasive OR invader OR introduced OR alien OR exotic OR non-native OR nonnative OR non-indigenous). We limited our search to papers published up to 2020. After the removal of duplicates, publications were evaluated by their title and abstract in the first screening, and through full reading in the second screening (Suppl. material 1). Papers were excluded if they:

i. did not conduct classical FR experiments (i.e. application of FR in mathematical models; using only a single resource density; did not estimate the parameters; did not model the type of curve; strictly investigated feeding preference);
ii. were observational studies (the initial densities and the consumption were not controlled, only estimated);
iii. did not use NNS in the experiments, either as a consumer or as a resource, or the NNS was only indirectly related (effect of their presence in the FR of a native species, for example);
iv. were in other languages than English;
v. were book chapters or other types of documents that did not present original data.

Despite the comparative FR approach being the reason that sparked interest in applying FR in invasion science, we found a variety of study frameworks beyond explicit native versus NNS comparisons. While all of these studies were included because they met the above criteria, they are not comparative *per se*. Thus, the term "FR approach" is used here to refer to any study in our review (i.e. that used a NNS as a consumer or resource in FR experiments), whereas the "comparative FR approach" refers only to those that clearly make a comparison between native and NNS.

## Data extraction and publication trends

Data were extracted through a full reading of the papers selected in the second screening (a list of the data extracted from each study is available in Suppl. material 2). To compare the trend of publications using FR in invasion science with publications concerning FR in general, a new search in the WoS database was performed using only the search term TOPIC = ("functional response*"), again up to 2020. The results were then filtered through the WoS website, as follows:

i. the Research Area filter was used to refine the search for ecological studies and to exclude mathematical modelling studies (corresponding to the first and second steps in our original search);
ii. the Languages filter was used to select only English papers (corresponding to the fourth step in our original search);
iii. the Document Types filter was used to exclude reviews and book chapters (corresponding to the fifth step of the original search).

To make this comparison between FR publications in invasion science and in general, we calculated the Activity Index (AI) (Caliman et al. 2010; Evangelista et al. 2014):

$$AI = \left(\frac{CY}{CT}\right) / \left(\frac{TY}{TT}\right) \quad (1)$$

where CY is the number of papers using FR in invasion science published in a given year; CT is the total number of papers using FR in invasion science published in all years; TY is the number of papers on FR in general published in a given year; and TT is the number of papers on FR in general published for all of the years studied. Considering this, AI = 1 indicates that papers on FR in invasion science were published at the same relative rate as those in the overall literature (in our case, publications that used FR in studies other than invasion science); AI > 1 indicates that papers on FR in invasion science were published at a higher relative rate compared to the overall literature; and AI < 1 indicates that papers on FR in invasion science were published at a relatively lower frequency compared to the overall literature. Due to the low number of papers that used FR in invasion science until the 1990s, we analysed the AI for the last 30 years. Journal trends were also analysed as an absolute and weighted number of publications *per* journal (Suppl. material 3).

## Study attributes

Papers were classified into three categories regarding their main aims: biological control, biotic resistance, or impact assessment. Papers about biological control tested the efficiency of a native or NNS as a biological control agent of a pest using FR experiments. Papers classified as biotic resistance tested the ability of a native consumer to consume a non-native resource. On the other hand, impact assessment papers used FR to predict or evaluate the effect of NNS as consumers or resources in different contexts. The type of interaction, whether predator-prey, host-parasitoid, herbivore-plant, filter-feeding, or plant-nutrient was recorded according to the authors' classification. Finally, the habitat where the experiment was performed was classified into freshwater, marine/brackish water, or terrestrial according to the methods described in each paper and the country where the study was conducted was recorded to identify geographic trends of FRs in invasion science.

A Pearson's chi-squared test of homogeneity was used to test if the frequency of studies was evenly distributed across the different types of interaction and habitats investigated. A chi-square test of independence was used to test for independence between these attributes and the study category (biological control, biotic resistance, or impact assessment).

## Taxonomic trends

The Latin names of the species used in the FR experiments were recorded. Some studies did not identify the consumer/resource to the species level, so we used the most specific classification given (whether family or genus). Some studies used more than one species in each case, so the number of species exceeded the number of studies. Each species used in the studies, whether as a consumer or as a resource, was classified into its corresponding coarse taxonomic group following Pyšek et al. (2008). A chi-square test of homogeneity was used to verify if the frequency of studies was evenly distributed through the taxonomic groups used, both as consumer and resource.

The origin of the species used as consumer and resource was defined according to the authors' own classification. Species classified as adventive, alien, exotic, immigrant, imported, invader, invasive, introduced, naturalised, non-indigenous, non-native, or novel, were considered here as "non-native" in origin. For species classified as pests, we checked their origin in the literature. Species described as endemic, indigenous, native, or natural were considered "native" in origin. When the origin of the species was not clearly stated in the text, the classification was searched elsewhere or considered as "non-identified" when it was not possible to confirm.

## Context-dependencies and FR types

A single study can perform more than one FR experiment under different contexts. Here, we recorded the number of different contexts used, as well as whether they are

biotic (such as life stage, starvation period, and sex) or abiotic (for example, temperature and habitat complexity), and which treatments were tested within each context (a list of treatments for each context is available at Suppl. material 4).

For each FR experiment, the FR type was identified through the text, tables, or figures according to the authors' classification. If the paper did not explicitly classify into one of the FR types, it was identified by the equation used to model the curve. For example, Rogers' random predator equation and Holling's disc equation were considered Type II FR, whereas Hassell's equation was considered Type III. Pearson's chi-squared tests of independence were used to test for independence between the FR curve type and the type of interaction, or the habitat studied. All analyses were performed in R v. 4.1.0 (R Core Team 2021), considering a significance level of alpha = 0.05.

## Results

### Literature search and screening

The search yielded 785 documents and the first screening through title and abstract was more conservative, so all potentially relevant papers were selected for the next step, totalling 175 papers. The second screening through full-text reading resulted in 120 papers included in the systematic review (Suppl. material 1; the list of all references included in the systematic review is available in Suppl. material 5).

### Publication trends

The first paper published in our survey of FRs in invasion science dates from 1966; however, this study investigated a non-native consumer FR without clearly aiming to assess impacts or test invasion hypotheses. Likewise, publications were generally rare (i.e. one or none *per* year) and strictly related to biological control until 2003 (Fig. 2A). The relative frequency of studies using FR in the context of invasion science only surpassed those of FR in general in 2014, corroborating the growth in the AI (Fig. 2B). Journal trends are presented in Suppl. material 3.

### Study attributes

Most of the studies were classified as impact assessment (62.5%), whereas 28.3% were categorised as biological control and 9.2% as biotic resistance. Studies investigating predator-prey interactions were by far the most common (76.7%), followed by host-parasitoid interactions (12.5%), herbivory (5.8%), and filter-feeding (4.2%), while plant-nutrient interactions were the least studied (0.8%). Therefore, the distribution of studies according to the type of interaction was not homogeneous ($\chi^2$ =245.2, df = 4, n = 120, $p < 0.001$), with predator-prey interactions predominantly featuring in impact assessment studies, and all studies of host-parasitoid interactions classified as biological

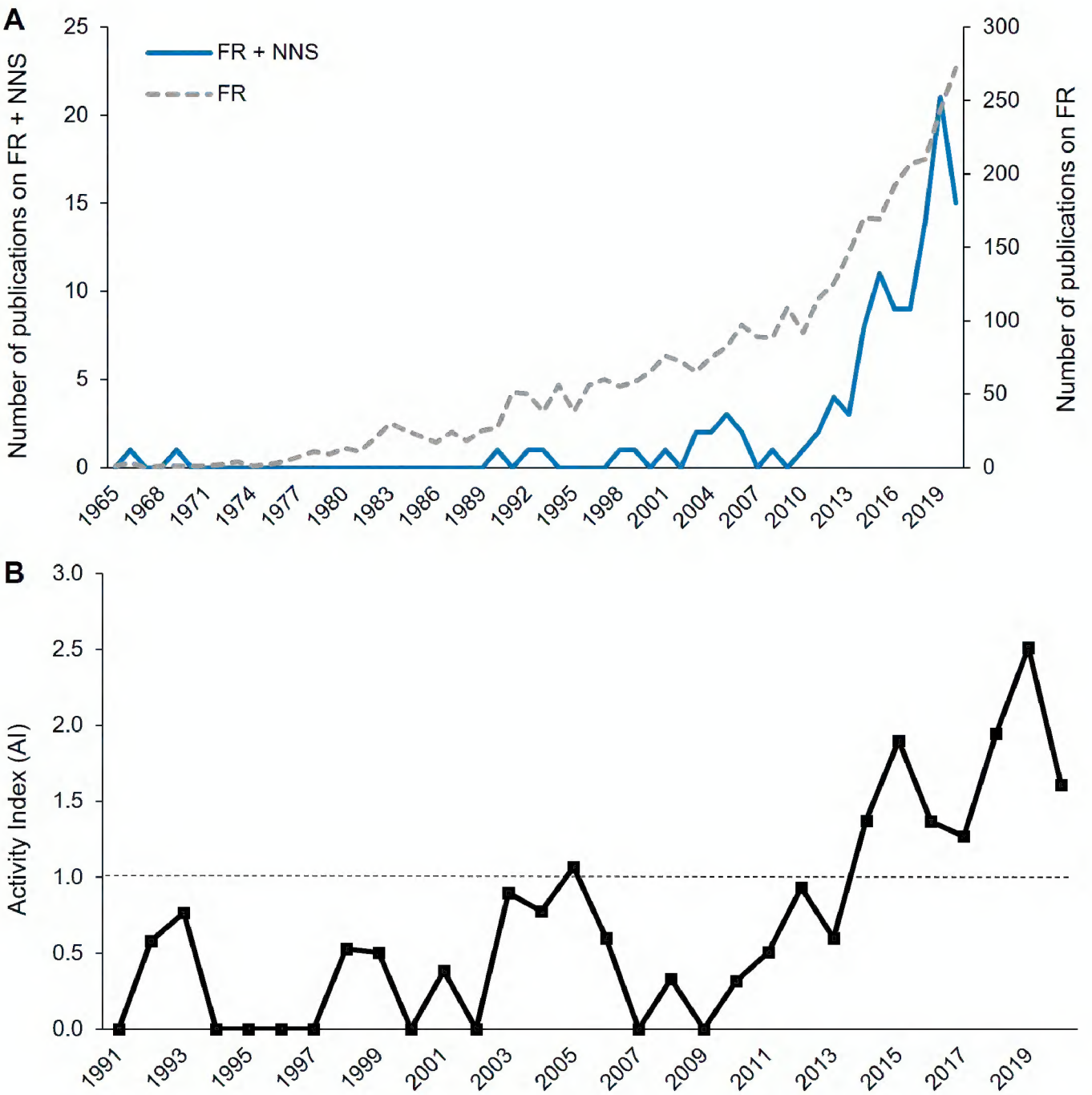


**Figure 2.** Temporal trends of papers using Functional Response in invasion science (i.e. FR + NNS) and Functional Response in general (FR) **A** number of published papers *per* year (please note the different scale on the right) **B** the Activity Index (AI) in research output that used Functional Response in the context of invasion science relative to all studies about Functional Response in general in the same period.

control ($\chi^2$ = 47.1, df = 8, n = 120, $p < 0.001$; Fig. 3). There are also significant differences regarding the type of habitat, as almost half of the studies featured freshwater environments (50.8%), followed by terrestrial (35.8%) and marine/brackish water (13.3%) ($\chi^2$ = 25.7, df = 2, n =120, $p < 0.001$). Most studies in the terrestrial environment were those classified as biological control (79%), whereas all the freshwater studies were classified as impact assessment or biotic resistance, and hence these two variables were not independent ($\chi^2$ = 92.8, df = 4, n = 120, $p < 0.001$; Fig. 3). Regarding geographic trends, most studies were conducted in the UK (n = 35), followed by USA (n = 20), Canada (n = 13), and China (n = 8). Six papers were conducted in more than one country and thus were counted more than once. Striking gaps in FR reporting from NNS were found across much of Asia, Africa, Eastern Europe, and South America (Fig. 4).

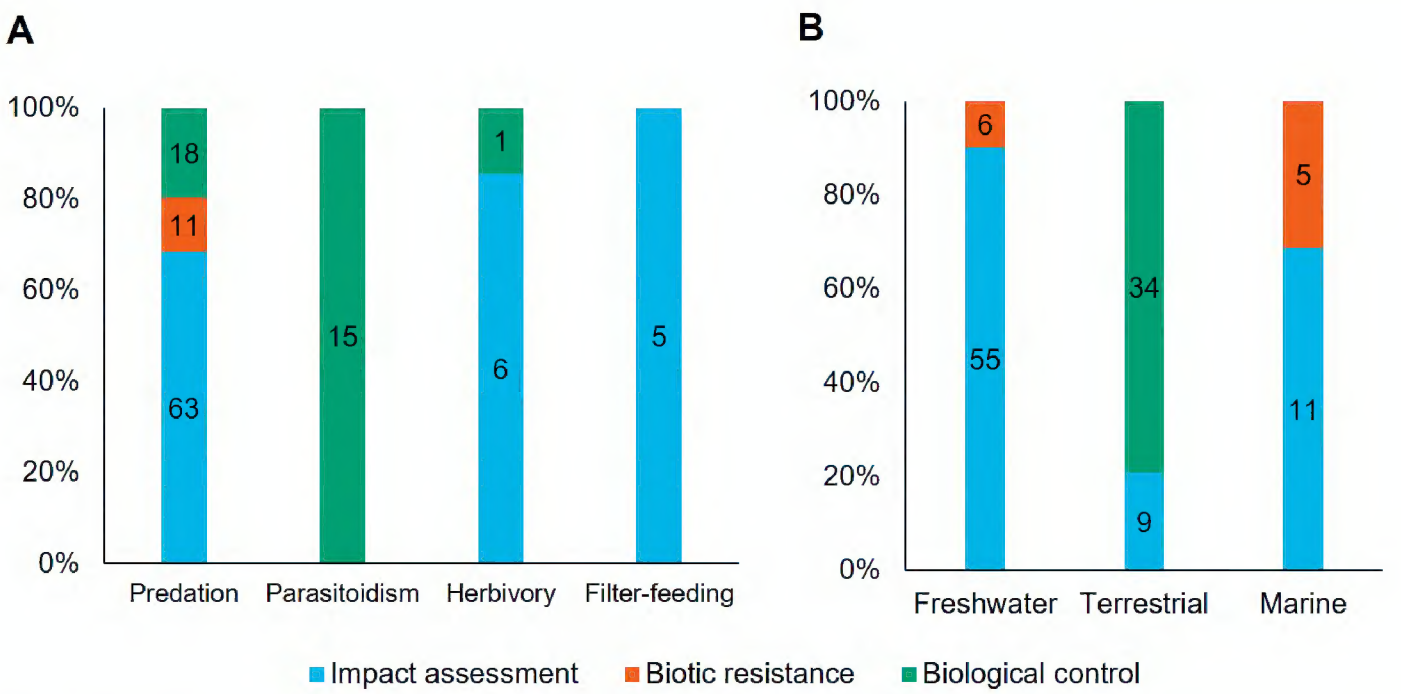


**Figure 3.** The proportion of studies *per* category **A** regarding type of interaction **B** regarding habitat type. The numbers inside the bars indicate the total number of papers. The plant-nutrient interaction type was omitted in plot **A** to facilitate visualisation (only one study in the freshwater environment).

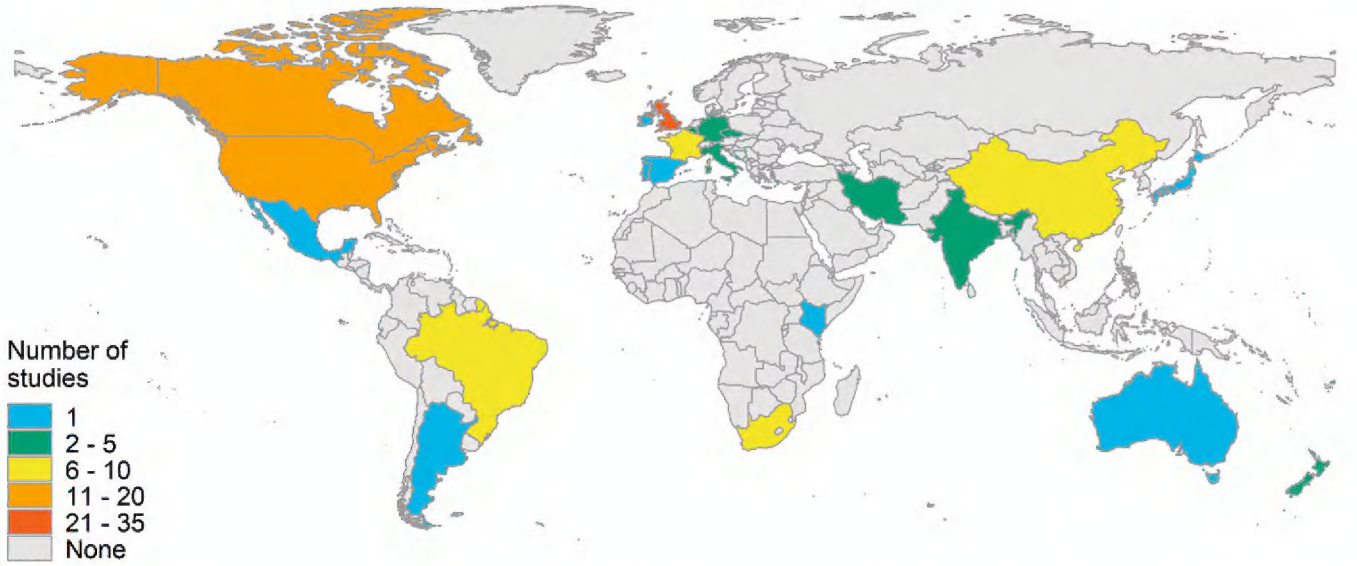


**Figure 4.** World map showing the number of studies conducted *per* country included in this review. Antarctica is omitted from the map but there are no studies conducted in this region.

## Taxonomic trends

In general, insects and crustaceans were the most studied taxonomic groups, both as consumers ($\chi^2 = 98.1$, df = 7, n = 122, $p < 0.001$) and as resource ($\chi^2 = 176.5$, df = 7, n = 134, $p < 0.001$), followed by fish and molluscs as consumers and resources, respectively (Fig. 5). Yet within crustaceans, gammarids (Gammaridae) comprised almost half (49%) of the studies using a crustacean as a consumer. Among biological control studies in the terrestrial habitat, investigations of host-parasitoid interactions were most common and always used insects as study species. Regarding impact assessment

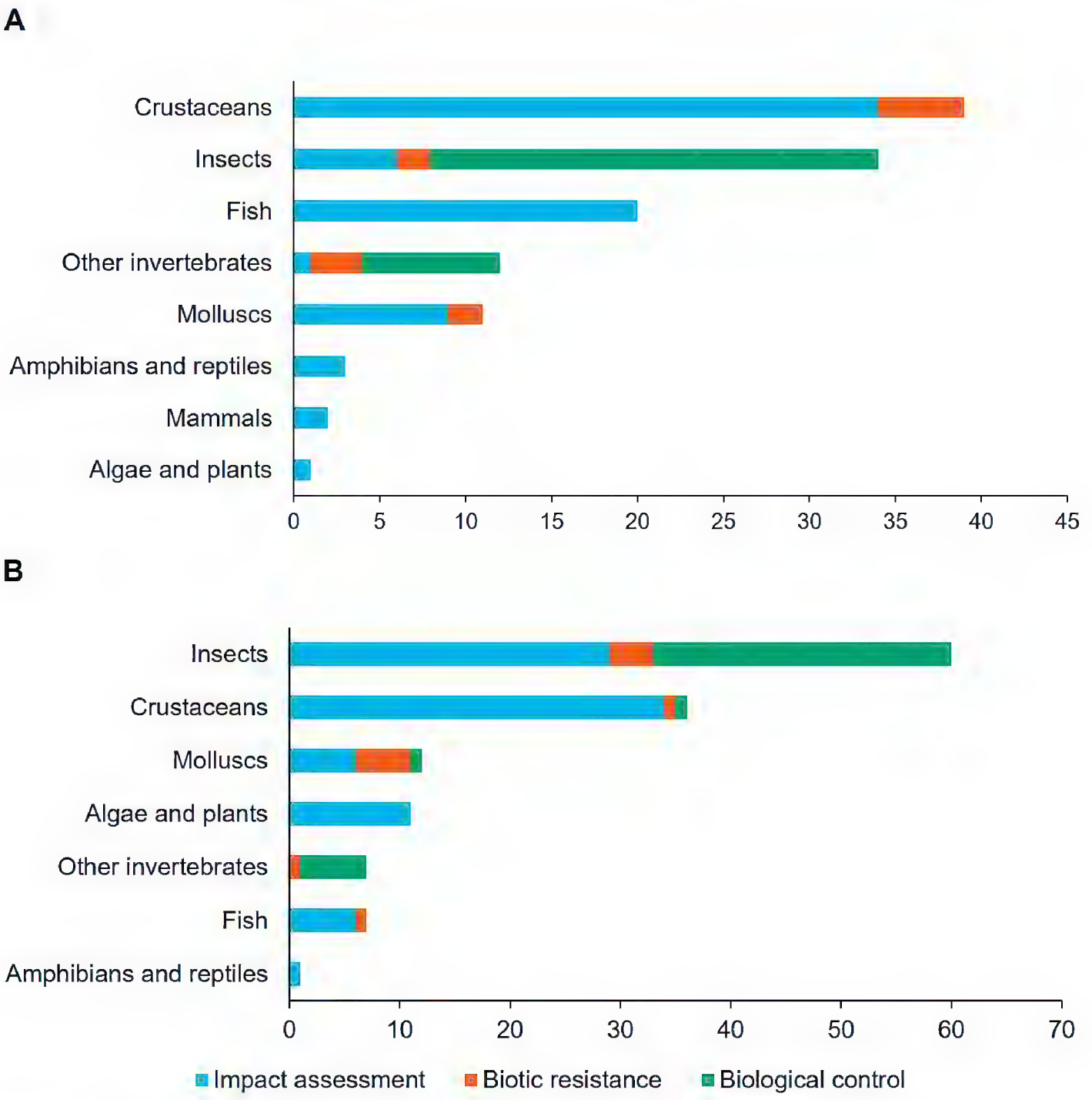


**Figure 5.** Frequency of studies for each taxonomic group considering the different study categories **A** regarding the consumer used **B** regarding the resource used. Studies that used species from different taxonomic groups were counted once for each case.

and biotic resistance studies, most investigations were related to predator-prey interactions, mainly using crustaceans and fish.

As some studies used more than one species as a consumer and/or resource, a total of 249 species were used in the FR experiments. Some species were used both as a consumer and as a resource, resulting in 147 species used as consumers and 112 as resources. Regarding consumer species, *Gammarus pulex* (Amphipoda: Gammaridae) (n = 15 studies) was most frequently used, followed by *Dikerogammarus villosus* (Amphipoda: Gammaridae) (n = 8), *Gammarus duebeni celticus* (Amphipoda: Gammaridae) (n = 6), and *Hemimysis anomala* (Mysida: Mysidae) and *Neogobius melanostomus* (Perciformes: Gobiidae), which were both used in five studies each. All other species were used in fewer than five studies. The species most commonly used as a resource was also

*G. pulex* (n = 9), followed by *Daphnia magna* (Diplostraca: Daphniidae) (n = 8), and *Asellus aquaticus* (Isopoda: Asellidae) and *Tuta absoluta* (Lepidoptera: Gelechiidae), which were both used in five studies each. All other species used as a resource were employed in fewer than five studies. In 22 studies, the resource was not identified at the species level, with Chironomidae larvae being most frequently employed (n = 14).

Most studies used non-native consumers (39.2%), or compared native and non-native consumers (38.3%), whereas 22.5% used a native consumer only. Regarding the resources, the greatest number of studies used only non-native resources (40.7%), whereas 18.6% of studies used native resources and 17.8% compared native and NNS. For some studies, it was not possible to identify the origin of the resource used, either in the text or in other sources (22.9%).

### Context-dependencies and FR types

Most studies (81.7%) considered context-dependency in their experimental design by modelling the FR under different biotic and abiotic treatments. From these, the majority tested biotic contexts (65.7%), followed by studies testing different abiotic contexts (20.2%), while just 14.1% used both biotic and abiotic treatments. Each study used from one to four different treatments, and because of that, the 120 papers yielded data from 735 FR curves. Among the biotic contexts, the most frequently used were consumer or resource origin (i.e. native or non-native), and life stage (Fig. 6). Regarding abiotic contexts, the most frequently tested were temperature and habitat complexity (Fig. 6).

Most of the 735 FR curves recorded were classified by the study as Type II (87.7%). Those classified as Type III accounted for 7% of the FR curves, and only 25 (3.4%) were classified as Type I. One study classified the curve as Type IV, whereas four studies did not clearly define the FR type in the text or figures, nor the type of equation used to model the FR. The type of interaction and the FR type are not independent, as Type II FRs were more common for all types of interaction except filter-feeding ($\chi^2 = 243.3$, df = 6, n = 717, $p < 0.001$). Type II was also the most common type of FR regardless of the type of habitat studied ($\chi^2 = 33.2$, df = 4, n = 717, $p < 0.001$).

## Discussion

The Functional Response can be applied broadly to any consumer-resource interaction, despite being classically used to understand how predation affects population dynamics (Jeschke et al. 2004). In recent years, this concept has gained attention due to its application in fields beyond population ecology, biological control, fisheries management and in particular, invasion science (Ricciardi et al. 2021). However, the rapidly growing number of invasion science studies that use FR have done so in environmentally, geographically and taxonomically restricted applications, thus impeding large-scale quantitative comparisons and tests of hypotheses across different contexts. There is a conspicuous bias in the geographic distribution of studies, reflecting a common trend

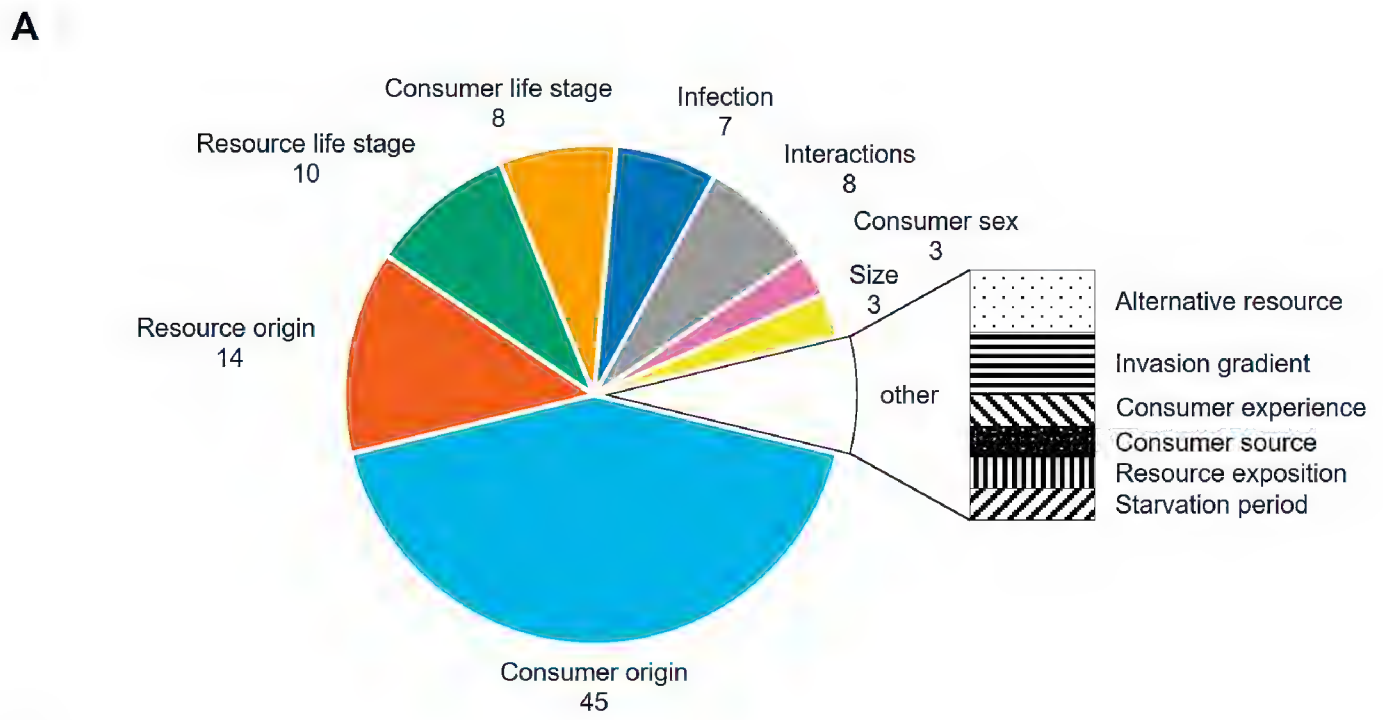


**Figure 6.** Different contexts used in experiments of the studies which derived Functional Responses under more than one treatment **A** regarding biotic contexts **B** regarding abiotic contexts. For biotic contexts, treatments used in two or fewer studies (alternative resource 2, invasion gradient 2, consumer experience 1, consumer source 1, resource exposition 1, and starvation period 1) were included in "other". For abiotic contexts, treatments used in only one study (depth, disturbance, field versus laboratory, light regime, period of the day, and site) were included in "other".

in invasion science (Pyšek et al. 2008; Bellard and Jeschke 2016). A limitation of our review is that we only searched for publications in English (Angulo et al. 2021); if we had included grey literature or used other repositories, we may have further broadened the geographic distribution of the reviewed papers. Nevertheless, we found that FR research has been geographically skewed towards North America and Europe (especially the United Kingdom), where research capacities are comparatively high, as well as towards predator-prey interactions in freshwater habitats, with a paucity of terrestrial and marine studies and other trophic and taxonomic groups. In turn, most studies have

focused on a few species of crustaceans, insects, molluscs, and fishes, and considered origin, life stage, temperature, and habitat complexity as principal context-dependencies.

Despite rapid growth in the FR approach in the last decade, the first study investigating the FR of a NNS (Mook and Davies 1966) was published only seven years after the seminal paper about FR by Holling (1959). The Activity Index (AI) showed that, after 2014, papers using FR in invasion science were published at a higher relative rate compared to the overall literature on FR (i.e. AI >1). This coincides with the publication of a series of seminal papers using FR in the context of invasion science between 2008 and 2014 (e.g. Bollache et al. 2008; Dick et al. 2013a; Alexander et al. 2014), culminating in the first paper formally outlining the use of the comparative FR as a methodology to predict NNS impacts (Dick et al. 2014). This suggests that the papers published in the period and empirical demonstrations of the method (e.g. Alexander et al. 2014) had a substantial impact in the field, generating a 'boom' of studies applying the FR approach in impact assessment of NNS, which was claimed to be a method capable of unifying invasion science (Dick et al. 2017a but see Vonesh et al. 2017; Griffen 2021).

Among study types, it was revealed that studies using the FR approach to demonstrate the impact of NNS were more common than those with a biological control focus or investigating biotic resistance. However, it is important to highlight that our search string was focused on invasion science terminology. Despite many pests being NNS, their origin is often disregarded in purely biological control studies, whereas studies that investigate NNS ecological impacts generally clearly state the non-native origin of the species. Therefore, we do not expect to have captured all studies that used FR in the biological control context, largely because of a different terminology (e.g. "pest" or "weed" species). There is also a difference in journals that typically publish these study types. For instance, we found that Biological Invasions and Biological Control were the journals with a higher number of publications of FRs in invasion science; however, the former published proportionally more impact assessment studies than the latter.

We found important biases regarding study attributes, such as the type of interaction and habitat investigated. Studies on the FR of predators are numerous, and this was somewhat expected given that predators are long recognised as damaging NNS (Salo et al. 2007; Paolucci et al. 2013). Also, the general idea of FR was classically applied to understand the effects of predators on prey population dynamics (Holling 1959; Oaten and Murdoch 1975) and in early work concerning FRs in invasion science (Bollache et al. 2008), although FR use was recognised in algal nutrient uptake (e.g. Tilman 1977) and herbivory (e.g. Farnsworth et al. 2002; Gioria and Osborne 2014). Thus, there is a historical bias towards the investigation of predator-prey interactions. This pattern is also found in a global compilation of FR data, where more than 90% of the compiled curves were from predators (FoRAGE database; Uiterwaal et al. 2022). The second most studied type of interaction was host-parasitoid, albeit always in biological control studies. As parasitoids are often specialists, this may explain their application to biological control investigations, mainly when trying to control an introduced pest that is released from its natural enemies in the invaded system (Hassell and Waage 1984). Despite this, it is important to highlight that FRs can be applied

to other forms of resource exploitation (including resources other than food), such as plant nutrient uptake, habitat conversion, shelter use, pollination of flowering plants, and so on (Dick et al. 2017a; Dickey et al. 2020). An example of its potential for diverse application is the employment of FRs to quantify the exploitation of invasive macrophyte as case-building material by larval caddisflies (Crane et al. 2021).

Another striking bias is the number of studies performed in the freshwater environment, given that the vast majority of NNS are in terrestrial ecosystems (Cuthbert et al. 2021), and most studies in invasion science focus on the terrestrial realm (Pyšek et al. 2008; Jeschke and Heger 2018). *A priori*, one might thus assume that there would be more FR studies of NNS in this realm. One potential driver for this prevalence of freshwater research could be the practicalities of measuring FRs in aquaria, for which methods have been well developed, in addition to the interests of active research groups in the field that use FR. However, experiments can also be easily performed in other environments, as evidenced by similar proportions of FR curves derived for marine, terrestrial and freshwater environments in the FoRAGE database (Uiterwaal et al. 2022), with greater research effort therefore needed to measure FRs of NNS in terrestrial and marine realms. When studying marine organisms, researchers can use artificial seawater in experimental setups similar to those applied in freshwater studies (e.g. Alexander et al. 2015; DeRoy et al. 2020). On the other hand, cages placed in the field can aid in investigating FRs of terrestrial organisms outside of the laboratory. For instance, Norbury and van Overmeire (2019) measured the predation rate of the invasive European hedgehog on native invertebrate prey, placing small cages in pastures of native and non-native vegetation.

The bias in habitat types is also reflected in the taxonomic groups and species used in the experiments. Crustaceans and insects are significantly more employed, not only as resources but also as consumers, a trend also observed in the FoRAGE database (Uiterwaal et al. 2022). Although it is not surprising regarding biological control studies, given that many pests are insects (as well as their respective predators and parasitoids; or weeds with insect agents), it is unexpected in the case of impact assessment and biotic resistance investigations. This may be explained by invertebrates being small-sized and easier to maintain in artificial environments such as laboratories. Additionally, many countries are faced with restrictions on the use of vertebrates in experimental studies, which may bias investigations towards invertebrate interactions. An alternative is to derive FRs using field data for vertebrate taxa (Goss-Custard et al. 2006; Smout et al. 2013) or through the use of quantitative PCR of gut contents. However, even when it is possible to use vertebrates in experiments, a common challenge is the number of organisms needed to perform sufficient replications under an adequate gradient of initial resource densities. Recently, novel approaches have been applied to quantify FR using fewer individuals, such as via measuring time between captures and gut content analysis (Mofu et al. 2019; Coblentz and DeLong 2021) which could allow FR studies to involve more practically challenging taxa (e.g. limited numbers, large-sized, ethically restricted).

The species most commonly used as both a consumer and a resource was *Gammarus pulex*, being already studied in a wide variety of contexts such as infection (Haddaway

et al. 2012; Bunke et al. 2019), temperature (Laverty et al. 2017), habitat complexity (Barrios-O'Neill et al. 2015), and substrate (Dodd et al. 2014; Cuthbert et al. 2019b). Moreover, we noticed a similar trend for freshwater crustaceans in general (gammarids, mysids, decapods), which may reflect their prevalence as invasive freshwater species (Gherardi 2007; Strayer 2010), as well as the value of these taxa as model organisms for predator-prey interactions. Several known impactful species, for example the walking catfish (*Clarias batrachus*) and the red imported fire ant (*Solenopsis invicta*), and rapidly spreading NNS such as the striped eel catfish (*Plotosus lineatus*), however, are still entirely understudied regarding their FRs. In particular, we found only one study measuring FRs of invasive plants, but this may relate to differences in terminology in terms of resource acquisition in plants (e.g. "uptake curves", Rossiter-Rachor et al. 2009; "resource use efficiency", Funk and Vitousek 2007; "nutrient responses", King and Wilson 2006).

Despite the comparison of the FR of non-native and native analogue consumers being proposed as a practical tool to predict and quantify the impacts of NNS, just half (53%) of the impact assessment studies have performed such a comparison. We highlight that the comparative FR approach is a phenomenological rather than a mechanistic method to understand impacts of NNS and should be interpreted relative to native trophic analogue consumers. When native analogues are absent, it can still be used within species as a response to different relevant contexts. For example, four studies compared the FR of the same species from different populations of its native and introduced ranges (Dick et al. 2013a; Howard et al. 2018; Boets et al. 2019; Grimm et al. 2020). Intraspecific inter-population comparisons in disparate geographical regions and eco-evolutionary contexts may help to shed light on the adaptive mechanisms of NNS that make them impactful in their introduced region. Moreover, impact assessments based on estimates from single populations or a single site could be misleading due to context-dependencies (Howard et al. 2018; Boets et al. 2019; Grimm et al. 2020), and further studies comparing multiple populations must be performed to understand sources of variation in *per capita* effects of the same species in different regions.

Indeed, the possibility of incorporating different context-dependencies in FR experiments is taken as one of the main advantages of this methodology in NNS impact prediction (Dick et al. 2014, 2017a). Several different biotic and abiotic variables can influence the FR (Holling 1959), and accordingly many studies use different treatments to simulate more realistic conditions when deriving FR curves for a species. The biotic contexts most investigated were the origin (native or non-native) of the consumer or resource species, which was expected given the studies targeted by this review. Following origin, the second most studied biotic context was the life stage. It is well known that the diet of a given species can change along with its ontogenetic development (Werner and Gilliam 1984) and reproductive cycle (Dalal et al. 2021), influencing the identity and quantity of the resources used. Additionally, the life stage is directly related to size, influencing the FR parameter of handling time and thus the maximum consumption rate (Vucic-Pestic et al. 2010; Barrios-O'Neill et al. 2016).

Ecological interactions such as cannibalism, intra-guild predation, competition, and higher-order predator presence (Paterson et al. 2015; Bunke et al. 2019; DeRoy et

al. 2020; Otturi et al. 2020) were among the most highly investigated biotic contexts. These contexts are critical for upscaling interactions to the ecosystem level where, for example, the presence of conspecifics or other species can lead to facilitation or interference (Griffen 2006; Médoc and Spataro 2015; Médoc et al. 2015), in turn directly influencing consumption rates. This is a feature that should be more often incorporated in future FR studies in the context of invasion science to provide realistic assessments (Griffen 2021).

In addition to biotic variables, the most tested abiotic contexts across studies were temperature and habitat complexity. Temperature has well-known effects on metabolism of ectothermic organisms (DeLong et al. 2018), directly influencing consumption rates across species. The general relationships between temperature and the FR parameters attack rate and handling time have become well established (Englund et al. 2011; Uiterwaal and DeLong 2020). They suggest that under future climate warming (IPCC 2021) the negative trophic effects of NNS will be exacerbated (Sorte et al. 2013). Many studies thus tested projected temperatures to better understand the impacts of non-native consumers in this scenario (Pellan et al. 2016; Gebauer et al. 2018; Kemp and Aldridge 2018).

Habitat complexity is also an important abiotic context, given its capability of changing the FR curve type. Complex environments create barriers between the consumer and the resource, particularly at low densities, which favours the observation of a Type III FR; whereas in simpler habitats it is common to observe Type II FRs (Alexander et al. 2012, 2015; Barrios-O'Neill et al. 2015). Furthermore, the simplified habitat of aquaria and cages used in experiments and their limited space intensifies consumer-resource encounters, likely resulting in higher consumption rates than those expected to be observed in natural conditions (Bergström and Englund 2004; Uiterwaal et al. 2019; Griffen 2021). However, rather than trying to derive "true" FRs of species, it is the comparison among species (i.e. relative FRs) that are of interest in this context. Indeed, relative FR values correspond with actual impact in the field; for example, NNS/native species FR disparities explained differential impacts of invasive mysids (Dick et al. 2013b).

From our set of 120 papers, we obtained data from 735 FR curves, with Type II the most commonly reported form, and this is considered the simplest curve to model (Jeschke et al. 2002, 2004). However, it is important to keep in mind that this curve type can again be a result of the simplified arena and limited space used to perform trials, or the absence of alternative resources and thus lack of switching opportunities (Kalinkat et al. 2023). However, we found that studies employing more complex habitats in the experiments do not frequently observe the expected change from Type II to Type III curves. These studies found that the FR magnitude (i.e. the maximum feeding rate) was higher in low complexity environments (Alexander et al. 2015; Norbury and van Overmeire 2019) or that the estimated parameters differed (South et al. 2017). Although Barrios-O'Neill et al. (2015) found subtle changes towards Type III in more complex environments when using a flexible FR model, the same data were also adequately categorised as Type II. This underlines the potential importance of other contexts that modulate FR form, such as prey preferences and switching in environments

with diverse prey assemblages (Murdoch 1969; Kalinkat et al. 2023). Typically, FR studies provide only one resource, therefore accentuating impacts and neglecting to consider more complex communities that could influence resource refugia.

The pattern of Type I FR being typical for filter-feeders (Jeschke et al. 2004) is often cited in the literature. Surprisingly, we found the most common curve type for filter feeders to be Type III, however this was heavily influenced by a single study which derived 16 FR curves under various treatments, from which 13 were classified as sigmoidal (Marescaux et al. 2016). When this study was excluded, Type I was indeed shown to be most common (10 FR curves from a total of 11) for filter feeders, however not exclusively, with examples encountered for parasitoids (Matadha et al. 2005; Savino et al. 2012; Wang et al. 2020) and predators (Kushner and Hovel 2006; Tilves et al. 2013; Benhadi-Marín et al. 2018; Poley et al. 2018).

Our results highlight some challenges in FR analysis in general. The classification of FR types and the correct estimation of parameters is not trivial and depends on data quality (i.e. enough number of replications and optimised initial resource densities). Indeed, there is still a lot of discussion in the literature around how to achieve a more accurate result based on data from laboratory experiments that are often heteroscedastic (Uszko et al. 2020; Papanikolaou et al. 2021). Flexible or generalised models, where a scaling component $q$ can assume values that range from a strict Type II FR ($q = 0$) gradually to a Type III ($q = 1$) can be useful to avoid a dichotomy among types (e.g. Mistri 2004; Kushner and Hovel 2006; Twardochleb et al. 2012; Joyce et al. 2020). The type of FR can nevertheless provide different information to the parameters in terms of theoretical resource stability implications (i.e. Type II FRs can be more destabilising to low-density resources than Type III FRs), thereby complementing information from FR parameters, which can be incomparable between different FR types and models. However, despite being complementary pieces of information, the magnitude of the FR curve, and therefore its parameters, can be more informative regarding the effect of the consumer on the resource population than the FR type, particularly in impact assessment studies (Boets et al. 2019). Indeed, it has been shown in previous studies that the maximum feeding rate ($1/h$) can predict damaging invaders, which is the rationale to use it as the *per capita* effect within the RIP metric (e.g. Dick et al. 2017b).

## Outlook and recommendations

This review shows that the use of FR in invasion science is increasing, particularly since the first paper conceptualising the comparative approach (Dick et al. 2014). Despite the burgeoning number of publications, FR studies are highly variable regarding their approaches, and there are pervasive biases in the geographic regions, taxonomic groups, and habitats being studied. Besides addressing the gaps and biases identified here, we propose other underexploited avenues for futures studies applying the comparative FR approach; some general areas of research as well as examples of hypotheses in invasion science that could be tested are presented in Table 1.

We have four primary recommendations to advance the use of the comparative FR approach in invasion science. First, invasion scientists should keep abreast of developments in the analysis of FR to refine their approaches. Despite the FR being a classical ecological concept, its application is still developing, with new studies proposing best practices, analysis protocols, and how parameters may be accurately estimated and interpreted (Rosenbaum and Rall 2018; Uszko et al. 2020; Novak and Stouffer 2021; Papanikolaou et al. 2021; Giacomini 2022). For example, research is needed to understand how different conversion efficiencies and background mortalities may affect the general pattern of FRs; and if so, how to consider this in the method. As proposed by Landi et al. (2022), short-term FR experiments can be paired with longer consumer growth response experiments, to check if changes in consumer biomass across resource densities are significantly different between consumers.

Second, future studies should embrace the possibility of including context-dependencies to provide more realism to experimental results. For instance, species usually have more than one type of resource available in natural environments and will often not be foraging alone, thus facing competition for resources with conspecifics and other species. The presence of alternative resources leading to prey switching can effectively change the FR curve type (Murdoch 1969), so it is important that we also unravel this during experimental trials. Additionally, we can use FR-based metrics to assess the impacts of NNS through competition for resources (Dickey et al. 2020). Thus, there is an urgent need to include alternative resources, and inter- and intraspecific competition in FR experiments to obtain more accurate and realistic assessments (e.g. Médoc et al. 2015; DeRoy et al. 2020; Otturi et al. 2020). Likewise, the source of the organisms used in the experiments needs attention. Many studies use resources (and even consumers) sourced from artificial suppliers such as aquaculture and pet retailers (e.g. South et al. 2017, 2019; Cuthbert et al. 2019a), but this may bias the results as the species have not coexisted naturally and likely respond differently to those in nature. If we want to understand real ecological impacts, it is fundamental to favour organisms sampled from the natural habitat whenever possible, with a special focus on ecologically relevant resources.

Third, we recommend that future studies use FR-based metrics to improve impact predictions. Given that FR considers only *per capita* effects, consideration of numerical responses or associated proxies could improve predictive efforts (e.g. by accounting for the influence of field abundance or reproductive efforts on impact), such as with the RIP metric (Dick et al. 2017b; Dickey et al. 2020). Differential numerical responses should be addressed in risk assessment studies, given that FRs from NNS and native comparators may often be similar or even greater for natives, but impacts can be explained by the higher abundances of non-natives. In turn, the RIP metric originally considered only the maximum consumption rate of the species, but a more intricate relationship of impact and FR parameters can exist. Given this, a useful metric is the Functional Response Ratio (FRR), which reveals impacts through the ratio between the FR parameters attack rate and handling time (i.e. FRR = $a/h$), and can be a reliable tool for risk assessment of new NNS (Cuthbert et al. 2019a).

**Table 1.** Examples of research topics and hypotheses related to non-native species (NNS) that could be explored using the comparative Functional Response (FR) approach. Further relevant hypotheses that could be explored can, for example, be found in Enders et al. (2020) and Daly et al. (2023).

| Topic | Application | Key references |
|---|---|---|
| Trophic interactions | Classical concepts including prey switching, omnivory, multiple and non-lethal predator effects, interaction strengths, and trophic cascades, can be measured and compared under different experimental contexts using the FR. | Alexander et al. 2012; Barrios-O'Neill et al. 2015, 2016; Iacarella et al. 2018 |
| Non-trophic interactions and behaviour | The effects of key behaviours such as aggression, activity, and boldness can be quantified by the FR, yielding predictive information on NNS success and ecological impacts. Competitive interactions (e.g. of omnivores) can be revealed using combinations of stable isotope metrics to quantify shifts in trophic niche space and comparative FRs to quantify interaction strengths. | Dominguez Almela et al. 2021; McGlade et al. 2022 |
| Ecomorphology and ecophysiology traits related to ecological impacts of NNS | As the FR can be a phenomenological approach, integrating ecomorphological traits (e.g. body size, feeding structures), metabolic rate measurements, or immunoassay analysis can provide mechanistic explanations for differences in consumption impacts, thus improving predictive capacity. | Naranjo and Hagler 2001; Taylor and Dunn 2018; Luger et al. 2020; Giacomini 2022 |
| Spatiotemporal variation in the impacts of NNS | Impact prediction based on estimates from single populations can be misleading if *per capita* effects vary greatly across space and time. Studies comparing variation in FRs across conspecific populations have tested the importance of the environmental context and, in some cases, revealed predictable patterns. Largescale geographical comparisons, thus far rare, could test fundamental questions such as whether predation intensity (e.g. attack rate) is higher in the tropics. | Dick et al. 2013b; Iacarella et al. 2015b, a; Howard et al. 2018; Grimm et al. 2020; Freestone et al. 2021 |
| Differential impact of invasive species based on biogeographic origin | In some situations, native species are considered invasives. The FR can be applied to compare the differential impact of NNS, whether invasive or not, to invasive native species. | Valéry et al. 2008; Simberloff et al. 2012; Cunico and Vitule 2014; Xu et al. 2016 |
| How consumer population abundance affects trophic impacts | While the FR considers only *per capita* effects, consideration of numerical responses or associated proxies in combined metrics improve predictive efforts. Furthermore, the FR can be derived under different combinations of consumer density. | Dick et al. 2017b; Iacarella et al. 2018; Dickey et al. 2020 |
| **Hypothesis** | **Prediction (in italics) and application** | **Key references** |
| Resource Consumption | *Successful NNS are often more efficient at exploiting key resources than functionally-similar native species.* Invasive and non-invasive NNS and trophically analogous native species could be compared with respect to *per capita* effects related to feeding efficiency and voracity (e.g. attack rate, handling time). | Funk and Vitousek 2007; Johnson et al. 2008; Morrison and Hay 2011; Dick et al. 2013b; Ricciardi et al. 2013; Gioria and Osborne 2014 |
| Biotic Resistance | *Diverse communities of native species (and previously established NNS) inhibit subsequent establishment, population growth, and impacts of subsequently introduced NNS through antagonistic interactions including competition and predation.* FR experiments can be used to measure the magnitude of consumptive effects of native consumers on NNS. | Twardochleb et al. 2012; MacNeil et al. 2013 |
| Invasional Meltdown | *NNS can facilitate one another in various ways to increase colonisation success, abundance, or performance, thereby causing an acceleration in the rate of invasion and increasing the likelihood of synergistic impacts.* FR experiments could compare interactions between NNS and native consumer-resource combinations, besides different combinations of NNS to reveal if impacts of co-occurring NNS are additive, antagonistic, or synergistic. | Simberloff and Von Holle 1999; Simberloff 2006a; Braga et al. 2020 |

| Hypothesis | Prediction (in italics) and application | Key references |
|---|---|---|
| Ecological Naïveté | *NNS will be more impactful if the recipient community do not share an eco-evolutionary experience with functionally similar species, being naïve to the novel species.* One can use the FR to test the prediction that prey exposed to novel generalist predators would be more likely to be destabilised by the interaction (i.e. FR Type II, with high maximum feeding rate), compared to prey that have experience with such predators. Similarly, comparisons of conspecific populations of NNS on islands and mainlands could be done to test the related hypothesis of increased susceptibility of prey in insular habitats. | Ebenhard 1988; Cox and Lima 2006; Saul and Jeschke 2015; Anton et al. 2020 |
| Enemy of My Enemy | *A NNS co-evolved enemy has a stronger negative effect on resident native species, thereby reducing biotic resistance.* The effect of parasites on *per capita* effects of NNS and natives could be used to evaluate competitive abilities with and without the presence of natural enemies. | Colautti et al. 2004; Dick et al. 2010; Toscano et al. 2014 |
| Enemy Inversion | *Co-evolved enemies of NNS are less harmful for them in the non-native than in the native range, due to altered biotic and abiotic conditions.* This hypothesis could be tested for predator-prey and herbivore-plant interactions in different biogeographic contexts using comparative FR experiments. | Colautti et al. 2004 |
| Evolution of Increased Competitive Ability | *The release or reduction of enemies that constrain a NNS population or performance in the native range can trigger the evolution of increased competitive traits in the introduced range.* This hypothesis could be tested through a comparison of FR *per capita* effects of conspecific populations in invaded and native ranges. | Blossey and Nötzold 1995 |
| Evolutionary Imbalance | *Successful and more competitive NNS are likely originating from geographic regions of high phylogenetic diversity.* FRs can compare *per capita* effects, and thus competitive abilities, of functionally or phylogenetically similar consumers from regions of contrasting diversity. | Fridley and Sax 2014 |
| Environmental Heterogeneity | *Spatiotemporal heterogeneity creates refugia against the impacts of NNS on native resources, thereby facilitating coexistence.* FR experiments can incorporate multiple levels and types of habitat complexity to compare its effects on trophic impacts of NNS. | Melbourne et al. 2007; Barrios-O'Neill et al. 2014 |
| Environmental Matching | *The impact of a NNS is inversely correlated with the distance of the novel habitat conditions from the species' environmental optimum.* FRs can be used to measure variation in *per capita* effects across physicochemical gradients in the lab and in the field. | Kestrup and Ricciardi 2009; Iacarella and Ricciardi 2015; Iacarella et al. 2015a |
| Invasion Front | *Individuals at the front of a spreading NNS population have higher resource consumption rates (leading to higher trophic impacts) than those from the well-established core population, owing to selection for reduced intraspecific competition at the core.* The comparative FR approach could be applied to test intraspecific differences in *per capita* effects across an expanding population to account for variation in impact across space and time. | Iacarella et al. 2015b |
| Taxonomic Distinctiveness | *NNS that belong to taxonomic groups (genera, families) that are not present historically in the invaded community are more likely to cause significant impacts on biodiversity, food webs, or ecosystem processes, owing to novel use of resources (see also Ecological Naïveté hypothesis).* The comparative FR approach can be used to test differences in the impacts of conspecific NNS populations in invaded communities that contain genera shared with the NSS versus those communities in which the NNS belong to a novel genus. | Ricciardi and Atkinson 2004 |

Our final recommendation is to unite disparate terminology in animal and plant research on FRs as well as between fields considering NNS (invasion science and biological control), as differences in nomenclature may impede us identifying patterns in NNS resource use among different taxa and study systems. This is an issue faced not only in ecology but in science in general (Hodges 2008; Jeschke et al. 2019), and polysemy may hinder our comprehensive understanding of NNS impacts across different types of interaction, simply because we cannot track relevant studies. For example, we found two papers that used the term "functional response" for assessing growth performance of plants (Radford et al. 2007; Radford 2013), so they did not meet the criteria to be included in our review. However, we may have conversely missed important studies with plants that used different terminology (e.g. uptake curves and nutrient responses).

There is still a long path to establish the comparative FR approach as a potential universal NNS impact assessment tool, but here we have aimed to advance this goal by revealing knowledge gaps and identifying potential fertile ground for research. We advocate that FR-based metrics can be included in official risk assessment protocols adopted by the IUCN, such as the Environmental Impact Classification for Alien Taxa (EICAT). Although useful to categorise species regarding its impacts, EICAT depends solely on invasion history which is not available for all NNS. The incorporation of FR in this analysis would potentially allow proactive rather than reactive management, while supporting white and blacklists of NNS (Simberloff 2006b).

As NNS can cause impact at any moment after introduction before going through the various invasion stages (e.g. Blackburn et al. 2011; Ricciardi et al. 2013), the FR approach can help target which species are more likely to cause harm before they become too entrenched to manage. In this sense, we conclude that the FR approach can also be valuable to disentangle the impacts of NNS from those of native species that eventually behave like invasives (i.e. increase their range and abundance), ultimately unravelling the role of biogeographic origin on consumptive and non-consumptive effects (Richardson and Ricciardi 2013; Simberloff and Vitule 2014).

## Acknowledgements

We thank Laís Carneiro for her precious help in making Fig. 4. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. RNC is funded by an Early Career Fellowship from the Leverhulme Trust (ECF-2021-001), JWED is funded by the Alexander von Humboldt Foundation, AR is funded by the Natural Sciences and Engineering Research Council of Canada, and JRSV is funded by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq – Process numbers 310850/2012-6; 303776/2015-3 and 302367/2018-7).

## References

Alexander ME, Dick JTA, O'Connor NE, Haddaway NR, Farnsworth KD (2012) Functional responses of the intertidal amphipod *Echinogammarus marinus*: Effects of prey supply, model selection and habitat complexity. Marine Ecology Progress Series 468: 191–202. https://doi.org/10.3354/meps09978

Alexander ME, Dick JTA, Weyl OLF, Robinson TB, Richardson DM (2014) Existing and emerging high impact invasive species are characterized by higher functional responses than natives. Biology Letters 10(2): 20130946. https://doi.org/10.1098/rsbl.2013.0946

Alexander ME, Kaiser H, Weyl OLF, Dick JTA (2015) Habitat simplification increases the impact of a freshwater invasive fish. Environmental Biology of Fishes 98(2): 477–486. https://doi.org/10.1007/s10641-014-0278-z

Angulo E, Diagne C, Ballesteros-Mejia L, Adamjy T, Ahmed DA, Akulov E, Banerjee AK, Capinha C, Dia CAKM, Dobigny G, Duboscq-Carra VG, Golivets M, Haubrock PJ, Heringer G, Kirichenko N, Kourantidou M, Liu C, Nuñez MA, Renault D, Roiz D, Taheri A, Verbrugge LNH, Watari Y, Xiong W, Courchamp F (2021) Non-English languages enrich scientific knowledge: The example of economic costs of biological invasions. The Science of the Total Environment 775: 144441. https://doi.org/10.1016/j.scitotenv.2020.144441

Anton A, Geraldi NR, Ricciardi A, Dick JTA (2020) Global determinants of prey naiveté to exotic predators. Proceedings of the Royal Society B 287. https://doi.org/10.1098/rspb.2019.2978

Ball SL, Woodcock BA, Potts SG, Heard MS (2015) Size matters: Body size determines functional responses of ground beetle interactions. Basic and Applied Ecology 16(7): 621–628. https://doi.org/10.1016/j.baae.2015.06.001

Barrios-O'Neill D, Dick JTA, Emmerson MC, Ricciardi A, MacIsaac HJ, Alexander ME, Bovy HC (2014) Fortune favours the bold: A higher predator reduces the impact of a native but not an invasive intermediate predator. Journal of Animal Ecology 83(3): 693–701. https://doi.org/10.1111/1365-2656.12155

Barrios-O'Neill D, Dick JTA, Emmerson MC, Ricciardi A, MacIsaac HJ (2015) Predator-free space, functional responses and biological invasions. Functional Ecology 29(3): 377–384. https://doi.org/10.1111/1365-2435.12347

Barrios-O'Neill D, Kelly R, Dick JTA, Ricciardi A, MacIsaac HJ, Emmerson MC (2016) On the context-dependent scaling of consumer feeding rates. Ecology Letters 19(6): 668–678. https://doi.org/10.1111/ele.12605

Bellard C, Jeschke J (2016) A spatial mismatch between invader impacts and research publications. Conservation Biology 30(1): 230–232. https://doi.org/10.1111/cobi.12611

Benhadi-Marín J, Pereira JA, Barreales D, Sousa JP, Santos SAP (2018) A simulation-based method to compare the pest suppression potential of predators: A case study with spiders. Biological Control 123: 87–96. https://doi.org/10.1016/j.biocontrol.2018.05.007

Bergström U, Englund G (2004) Spatial scale, heterogeneity and functional responses. Journal of Animal Ecology 73(3): 487–493. https://doi.org/10.1111/j.0021-8790.2004.00823.x

Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, Jarošík V, Wilson JRU, Richardson DM (2011) A proposed unified framework for biological invasions. Trends in Ecology & Evolution 26(7): 333–339. https://doi.org/10.1016/j.tree.2011.03.023

Blossey B, Nötzold R (1995) Evolution of increased competitive ability in invasive non-indigenous plants: A hypothesis. Journal of Ecology 83(5): 887–889. https://doi.org/10.2307/2261425

Boets P, Laverty C, Fukuda S, Verreycken H, Green K, Britton RJ, Caffrey J, Goethals PLM, Pegg J, Médoc V, Dick JTA (2019) Intra- and intercontinental variation in the functional responses of a high impact alien invasive fish. Biological Invasions 21(5): 1751–1762. https://doi.org/10.1007/s10530-019-01932-y

Bollache L, Dick JTA, Farnsworth KD, Montgomery WI (2008) Comparison of the functional responses of invasive and native amphipods. Biology Letters 4(2): 166–169. https://doi.org/10.1098/rsbl.2007.0554

Braga RR, Gómez-Aparicio L, Heger T, Vitule JRS, Jeschke JM (2017) Structuring evidence for invasional meltdown: Broad support but with biases and gaps. Biological Invasions 20(4): 923–936. https://doi.org/10.1007/s10530-017-1582-2

Braga RR, Ribeiro VM, Padial AA, Thomaz SM, Affonso IP, Wojciechowski J, Ribas LGS, Cunha ER, Tiburcio VG, Vitule JRS (2020) Invasional meltdown: An experimental test and a framework to distinguish synergistic, additive, and antagonistic effects. Hydrobiologia 847(7): 1603–1618. https://doi.org/10.1007/s10750-019-04107-x

Bunke M, Dick JTA, Hatcher MJ, Dunn AM (2019) Parasites influence cannibalistic and predatory interactions within and between native and invasive amphipods. Diseases of Aquatic Organisms 136(1): 79–86. https://doi.org/10.3354/dao03415

Caliman A, Pires AF, Esteves FA, Bozelli RL, Farjalla VF (2010) The prominence of and biases in biodiversity and ecosystem functioning research. Biodiversity and Conservation 19(3): 651–664. https://doi.org/10.1007/s10531-009-9725-0

Catford JA, Jansson R, Nilsson C (2009) Reducing redundancy in invasion ecology by integrating hypotheses into a single theoretical framework. Diversity & Distributions 15(1): 22–40. https://doi.org/10.1111/j.1472-4642.2008.00521.x

Coblentz KE, DeLong JP (2021) Estimating predator functional responses using the times between prey captures. Ecology 102(4): e03307. https://doi.org/10.1002/ecy.3307

Colautti RI, Ricciardi A, Grigorovich IA, MacIsaac HJ (2004) Is invasion success explained by the enemy release hypothesis? Ecology Letters 7(8): 721–733. https://doi.org/10.1111/j.1461-0248.2004.00616.x

Cox JG, Lima SL (2006) Naiveté and an aquatic-terrestrial dichotomy in the effects of introduced predators. Trends in Ecology & Evolution 21(12): 674–680. https://doi.org/10.1016/j.tree.2006.07.011

Crane K, Cuthbert RN, Ricciardi A, Kregting L, Coughlan NE, MacIsaac HJ, Reid N, Dick JTA (2021) Gimme shelter: Differential utilisation and propagule creation of invasive macrophytes by native caddisfly larvae. Biological Invasions 23(1): 95–109. https://doi.org/10.1007/s10530-020-02358-7

Crystal-Ornelas R, Lockwood JL (2020) The 'known unknowns' of invasive species impact measurement. Biological Invasions 22(4): 1513–1525. https://doi.org/10.1007/s10530-020-02200-0

Cunico AM, Vitule JRS (2014) First records of the European catfish, *Silurus glanis* Linnaeus, 1758 in the Americas (Brazil). BioInvasions Records 3(2): 117–122. https://doi.org/10.3391/bir.2014.3.2.10

Cuthbert RN, Dickey JWE, Coughlan NE, Joyce PWS, Dick JTA (2019a) The Functional Response Ratio (FRR): Advancing comparative metrics for predicting the ecological impacts of invasive alien species. Biological Invasions 21(8): 2543–2547. https://doi.org/10.1007/s10530-019-02002-z

Cuthbert RN, Coughlan NE, Dickey JWE, Rea M, Laverty C, South J, Crane K, McCard M, Dick JTA (2019b) Shell shocked: High potential impacts on native prey by non-native turtles irrespective of benthic habitat context. Aquatic Invasions 14(4): 758–774. https://doi.org/10.3391/ai.2019.14.4.13

Cuthbert RN, Pattison Z, Taylor NG, Verbrugge L, Diagne C, Ahmed DA, Leroy B, Angulo E, Briski E, Capinha C, Catford JA, Dalu T, Essl F, Gozlan RE, Haubrock PJ, Kourantidou M, Kramer AM, Renault D, Wasserman RJ, Courchamp F (2021) Global economic costs of aquatic invasive alien species. The Science of the Total Environment 775: 145238. https://doi.org/10.1016/j.scitotenv.2021.145238

Dalal A, Gallogly J, Cuthbert RN, Laverty C, Dickey JWE, Dick JTA (2021) Ecological impacts of an invasive predator are mediated by the reproductive cycle. Biological Invasions 23(3): 669–675. https://doi.org/10.1007/s10530-020-02414-2

Daly EZ, Chabrerie O, Massol F, Facon B, Hess MCM, Tasiemski A, Grandjean F, Chauvat M, Viard F, Forey E, Folcher L, Buisson E, Boivin T, Baltora-Rosset S, Ulmer R, Gibert P, Thiébaut G, Pantel JH, Heger T, Richardson DM, Renault D (2023) A synthesis of biological invasion hypotheses associated with the introduction–naturalisation–invasion continuum. Oikos e09645. https://doi.org/10.1111/oik.09645

DeLong JP, Bachman G, Gibert JP, Luhring TM, Montooth KL, Neyer A, Reed B (2018) Habitat, latitude and body mass influence the temperature dependence of metabolic rate. Biology Letters 14(8): 20180442. https://doi.org/10.1098/rsbl.2018.0442

DeRoy EM, Scott R, Hussey NE, MacIsaac HJ (2020) Density dependence mediates the ecological impact of an invasive fish. Diversity & Distributions 26(7): 867–880. https://doi.org/10.1111/ddi.13063

Diagne C, Leroy B, Vaissière AC, Gozlan RE, Roiz D, Jarić I, Salles JM, Bradshaw CJA, Courchamp F (2021) High and rising economic costs of biological invasions worldwide. Nature 592(7855): 571–576. https://doi.org/10.1038/s41586-021-03405-6

Dick JTA, Armstrong M, Clarke HC, Farnsworth KD, Hatcher MJ, Ennis M, Kelly A, Dunn AM (2010) Parasitism may enhance rather than reduce the predatory impact of an invader. Biology Letters 6(5): 636–638. https://doi.org/10.1098/rsbl.2010.0171

Dick JTA, Gallagher K, Avlijas S, Clarke HC, Lewis SE, Leung S, Minchin D, Caffrey J, Alexander ME, Maguire C, Harrod C, Reid N, Haddaway NR, Farnsworth KD, Penk M, Ricciardi A (2013a) Ecological impacts of an invasive predator explained and predicted by comparative functional responses. Biological Invasions 15(4): 837–846. https://doi.org/10.1007/s10530-012-0332-8

Dick JTA, Alexander ME, MacNeil C (2013b) Natural born killers: An invasive amphipod is predatory throughout its life-history. Biological Invasions 15(2): 309–313. https://doi.org/10.1007/s10530-012-0287-9

Dick JTA, Alexander ME, Jeschke J, Ricciardi A, MacIsaac HJ, Robinson TB, Kumschick S, Weyl OLF, Dunn AM, Hatcher MJ, Paterson RA, Farnsworth KD, Richardson DM (2014) Advancing impact prediction and hypothesis testing in invasion ecology using a comparative functional response approach. Biological Invasions 16(4): 735–753. https://doi.org/10.1007/s10530-013-0550-8

Dick JTA, Alexander ME, Ricciardi A, Laverty C, Downey PO, Xu M, Jeschke J, Saul W-C, Hill MP, Wasserman R, Barrios-O'Neill D, Weyl OLF, Shaw RH (2017a) Functional responses can unify invasion ecology. Biological Invasions 19(5): 1667–1672. https://doi.org/10.1007/s10530-016-1355-3

Dick JTA, Laverty C, Lennon JJ, Barrios-O'Neill D, Mensink PJ, Britton JR, Médoc V, Boets P, Alexander ME, Taylor NG, Dunn AM, Hatcher MJ, Rosewarne PJ, Crookes S, MacIsaac HJ, Xu M, Ricciardi A, Wasserman RJ, Ellender BR, Weyl OLF, Lucy FE, Banks PB, Dodd JA, MacNeil C, Penk M, Aldridge DC, Caffrey JM (2017b) Invader Relative Impact Potential: A new metric to understand and predict the ecological impacts of existing, emerging and future invasive alien species. Journal of Applied Ecology 54(4): 1259–1267. https://doi.org/10.1111/1365-2664.12849

Dickey JWE, Cuthbert RN, South J, Britton JR, Caffrey J, Chang X, Crane K, Coughlan NE, Fadaei E, Farnsworth KD, Ismar-Rebitz SMH, Joyce PWS, Julius M, Laverty C, Lucy FE, MacIsaac HJ, McCard M, McGlade CLO, Reid N, Ricciardi A, Wasserman RJ, Weyl OLF, Dick JTA (2020) On the RIP: Using Relative Impact Potential to assess the ecological impacts of invasive alien species. NeoBiota 55: 27–60. https://doi.org/10.3897/neobiota.55.49547

Dickey JWE, Arnott G, McGlade CLO, Moore A, Riddell GE, Dick JTA (2022) Threats at home? Assessing the potential ecological impacts and risks of commonly traded pet fishes. NeoBiota 73: 109–136. https://doi.org/10.3897/neobiota.73.80542

Dodd JA, Dick JTA, Alexander ME, MacNeil C, Dunn AM, Aldridge DC (2014) Predicting the ecological impacts of a new freshwater invader: Functional responses and prey selectivity of the "killer shrimp", *Dikerogammarus villosus*, compared to the native *Gammarus pulex*. Freshwater Biology 59(2): 337–352. https://doi.org/10.1111/fwb.12268

Dominguez Almela V, South J, Britton JR (2021) Predicting the competitive interactions and trophic niche consequences of a globally invasive fish with threatened native species. Journal of Animal Ecology 90(11): 2651–2662. https://doi.org/10.1111/1365-2656.13571

Ebenhard T (1988) Introduced birds and mammals and their ecological effects. Viltrevy (Stockholm) 13: 1–107. [Swedish Wildlife Research]

Eby LA, Rudstam LG, Kitchell JF (1995) Predator responses to prey population dynamics: An empirical analysis based on Lake Trout growth rates. Canadian Journal of Fisheries and Aquatic Sciences 52(7): 1564–1571. https://doi.org/10.1139/f95-149

Eggleston DB, Johnson EG, Kellison GT, Nadeau DA (2003) Intense removal and non-saturating functional responses by recreational divers on spiny lobster *Panulirus argus*. Marine Ecology Progress Series 257: 197–207. https://doi.org/10.3354/meps257197

Enders M, Havemann F, Ruland F, Bernard-Verdier M, Catford JA, Gómez-Aparicio L, Haider S, Heger T, Kueffer C, Kühn I, Meyerson LA, Musseau C, Novoa A, Ricciardi A, Sagouis A, Schittko C, Strayer DL, Vilà M, Essl F, Hulme PE, van Kleunen M, Kumschick S, Lockwood JL, Mabey AL, McGeoch MA, Palma E, Pyšek P, Saul WC, Yannelli FA, Jeschke

JM (2020) A conceptual map of invasion biology: Integrating hypotheses into a consensus network. Global Ecology and Biogeography 29(6): 978–991. https://doi.org/10.1111/geb.13082

Englund G, Öhlund G, Hein CL, Diehl S (2011) Temperature dependence of the functional response. Ecology Letters 14(9): 914–921. https://doi.org/10.1111/j.1461-0248.2011.01661.x

Evangelista HBA, Thomaz SM, Umetsu CA (2014) An analysis of publications on invasive macrophytes in aquatic ecosystems. Aquatic Invasions 9(4): 521–528. https://doi.org/10.3391/ai.2014.9.4.10

Farnsworth KD, Focardi S, Beecham JA (2002) Grassland-herbivore interactions: How do grazers coexist? American Naturalist 159(1): 24–39. https://doi.org/10.1086/324114

Freestone AL, Torchin ME, Jurgens LJ, Bonfim M, López DP, Repetto MF, Schlöder C, Sewall BJ, Ruiz GM (2021) Stronger predation intensity and impact on prey communities in the tropics. Ecology 102(8): e03428. https://doi.org/10.1002/ecy.3428

Fridley JD, Sax DF (2014) The imbalance of nature: Revisiting a Darwinian framework for invasion biology. Global Ecology and Biogeography 23(11): 1157–1166. https://doi.org/10.1111/geb.12221

Funk JL, Vitousek PM (2007) Resource-use efficiency and plant invasion in low-resource systems. Nature 446(7139): 1079–1081. https://doi.org/10.1038/nature05719

Gebauer R, Veselý L, Kouba A, Buric M, Drozd B (2018) Forecasting impact of existing and emerging invasive gobiids under temperature change using comparative functional responses. Aquatic Invasions 13(2): 289–297. https://doi.org/10.3391/ai.2018.13.2.09

Gherardi F (2007) Biological invaders in inland waters: Profiles, distribution, and threats. Springer, Dordrecht, 733 pp. https://doi.org/10.1007/978-1-4020-6029-8

Giacomini HC (2022) Metabolic responses of predators to prey density. Frontiers in Ecology and Evolution 10: 980812. https://doi.org/10.3389/fevo.2022.980812

Gioria M, Osborne BA (2014) Resource competition in plant invasions: Emerging patterns and research needs. Frontiers in Plant Science 5: 501. https://doi.org/10.3389/fpls.2014.00501

Goss-Custard JD, West AD, Yates MG, Caldow RWG, Stillman RA, Bardsley L, Castilla J, Castro M, Dierschke V, Durell SEALV, Eichhorn G, Ens BJ, Exo K-M, Udayangani-Fernando PU, Ferns PN, Hockey PAR, Gill JA, Johnstone I, Kalejta-Summers B, Masero JA, Moreira F, Nagarajan RV, Owens IPF, Pacheco C, Perez-Hurtado A, Rogers D, Scheiffarth G, Sitters H, Sutherland WJ, Triplet P, Worrall DH, Zharikov Y, Zwarts L, Pettifor RA (2006) Intake rates and the functional response in shorebirds (Charadriiformes) eating macro-invertebrates. Biological Reviews of the Cambridge Philosophical Society 81(4): 501–529. https://doi.org/10.1017/S1464793106007093

Griffen BD (2006) Detecting emergent effects of multiple predator species. Oecologia 148(4): 702–709. https://doi.org/10.1007/s00442-006-0414-3

Griffen BD (2021) Considerations when applying the consumer functional response measured under artificial conditions. Frontiers in Ecology and Evolution 9: 713147. https://doi.org/10.3389/fevo.2021.713147

Grimm J, Dick JTA, Verreycken H, Jeschke JM, Linzmaier SM, Ricciardi A (2020) Context-dependent differences in the functional responses of conspecific native and non-native crayfishes. NeoBiota 54: 71–88. https://doi.org/10.3897/neobiota.54.38668

Haddaway NR, Wilcox RH, Heptonstall REA, Griffiths HM, Mortimer RJG, Christmas M, Dunn AM (2012) Predatory functional response and prey choice identify predation differences between native/invasive and parasitised/unparasitised crayfish. PLoS ONE 7(2): e32229. https://doi.org/10.1371/journal.pone.0032229

Hassell MP, Waage JK (1984) Host-parasitoid population interactions. Annual Review of Entomology 29(1): 89–114. https://doi.org/10.1146/annurev.en.29.010184.000513

Heikinheimo O (2001) Effect of predation on the low-density dynamics of vendace: Significance of the functional response. Canadian Journal of Fisheries and Aquatic Sciences 58(10): 1909–1923. https://doi.org/10.1139/f01-132

Hodges KE (2008) Defining the problem: Terminology and progress in ecology. Frontiers in Ecology and the Environment 6(1): 35–42. https://doi.org/10.1890/060108

Holling CS (1959) The components of predation as revealed by a study of small-mammal predation of the European pine sawfly. Canadian Entomologist 91(5): 234–261. https://doi.org/10.4039/Ent91293-5

Howard BR, Barrios-O'Neill D, Alexander ME, Dick JTA, Therriault TW, Robinson TB, Côté IM (2018) Functional responses of a cosmopolitan invader demonstrate intraspecific variability in consumer-resource dynamics. PeerJ 6: e5634. https://doi.org/10.7717/peerj.5634

Iacarella JC, Ricciardi A (2015) Dissolved ions mediate body mass gain and predatory response of an invasive fish. Biological Invasions 17(11): 3237–3246. https://doi.org/10.1007/s10530-015-0949-5

Iacarella JC, Dick JTA, Ricciardi A (2015a) A spatio-temporal contrast of the predatory impact of an invasive freshwater crustacean. Diversity & Distributions 21(7): 803–812. https://doi.org/10.1111/ddi.12318

Iacarella JC, Dick JTA, Alexander ME, Ricciardi A (2015b) Ecological impacts of invasive alien species along temperature gradients: Testing the role of environmental matching. Ecological Applications 25(3): 706–716. https://doi.org/10.1890/14-0545.1

Iacarella JC, Hudgins EJ, Dick JTA, Ricciardi A (2018) Predatory behaviour of an invasive amphipod in response to varying conspecific densities under higher-order predation risk. Canadian Journal of Fisheries and Aquatic Sciences 75(1): 131–140. https://doi.org/10.1139/cjfas-2016-0417

IPCC (2021) Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, et al. (Eds) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, 3–32. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

Jeschke JM, Heger T (2018) Invasion Biology: Hypotheses and Evidence. CABI, Boston, MA. https://doi.org/10.1079/9781780647647.0000

Jeschke JM, Kopp M, Tollrian R (2002) Predator functional responses: Discriminating between handling and digesting prey. Ecological Monographs 72(1): 95–112. https://doi.org/10.1890/0012-9615(2002)072[0095:PFRDBH]2.0.CO;2

Jeschke J, Kopp M, Tollrian R (2004) Consumer-food systems: Why type I functional responses are exclusive to filter feeders. Biological Reviews of the Cambridge Philosophical Society 79(2): 337–349. https://doi.org/10.1017/S1464793103006286

Jeschke JM, Lokatis S, Bartram I, Tockner K (2019) Knowledge in the dark: Scientific challenges and ways forward. Facets 4(1): 423–441. https://doi.org/10.1139/facets-2019-0007

Johnson BM, Carpenter SR (1994) Functional and numerical responses – a framework for fish-angler interactions. Ecological Applications 4(4): 808–821. https://doi.org/10.2307/1942010

Johnson BM, Martinez PJ, Hawkins JA, Bestgen KR (2008) Ranking predatory threats by nonnative fishes in the Yampa River, Colorado, via bioenergetics modeling. North American Journal of Fisheries Management 28(6): 1941–1953. https://doi.org/10.1577/M07-199.1

Joyce PWS, Dick JTA, Kregting LT (2020) Lack of biotic resistance to an invasive bivalve irrespective of season or hydrodynamic disturbance. Journal of Experimental Marine Biology and Ecology 528: 151382. https://doi.org/10.1016/j.jembe.2020.151382

Kalinkat G, Rall BC, Uiterwaal SF, Uszko W (2023) Empirical evidence of type III functional responses and why it remains rare. Frontiers in Ecology and Evolution 11: 1033818. https://doi.org/10.3389/fevo.2023.1033818

Kemp JS, Aldridge DC (2018) Comparative functional responses to explain the impact of sympatric invasive bivalves (*Dreissena* spp.) under different thermal regimes. The Journal of Molluscan Studies 84(2): 175–181. https://doi.org/10.1093/mollus/eyy006

Kestrup ÅM, Ricciardi A (2009) Environmental heterogeneity limits the local dominance of an invasive freshwater crustacean. Biological Invasions 11(9): 2095–2105. https://doi.org/10.1007/s10530-009-9490-8

King WMCG, Wilson JB (2006) Differentiation between native and exotic plant species from a dry grassland: fundamental responses to resource availability, and growth rates. Austral Ecology 31(8): 996–1004. https://doi.org/10.1111/j.1442-9993.2006.01693.x

Kumschick S, Gaertner M, Vilà M, Essl F, Jeschke J, Pyšek P, Ricciardi A, Bacher S, Blackburn TM, Dick JTA, Evans T, Hulme PE, Kühn I, Mrugala A, Pergl J, Rabitsch W, Richardson DM, Sendek A, Winter M (2015) Ecological impacts of alien species: Quantification, scope, caveats, and recommendations. Bioscience 65(1): 55–63. https://doi.org/10.1093/biosci/biu193

Kushner RB, Hovel KA (2006) Effects of native predators and eelgrass habitat structure on the introduced Asian mussel *Musculista senhousia* (Benson in Cantor) in southern California. Journal of Experimental Marine Biology and Ecology 332(2): 166–177. https://doi.org/10.1016/j.jembe.2005.11.011

Landi P, McCoy MW, Vonesh JR (2022) Predicting invasive consumer impact via the comparative functional response approach: Linking application to ecological theory. Biological Invasions 24(11): 3565–3579. https://doi.org/10.1007/s10530-022-02862-y

Latombe G, Catford JA, Essl F, Lenzner B, Richardson DM, Wilson JRU, McGeoch MA (2022) GIRAE: A generalised approach for linking the total impact of invasion to species' range, abundance and per-unit effects. Biological Invasions 24(10): 3147–3167. https://doi.org/10.1007/s10530-022-02836-0

Laverty C, Brenner D, McIlwaine C, Lennon JJ, Dick JTA, Lucy FE, Christian KA (2017) Temperature rise and parasitic infection interact to increase the impact of an invasive species. International Journal for Parasitology 47(5): 291–296. https://doi.org/10.1016/j.ijpara.2016.12.004

Luger AM, South J, Alexander ME, Ellender BR, Weyl OLF, Nagelkerke LAJ (2020) Ecomorphology of largemouth bass relative to a native trophic analogue explains its high invasive impact. Biological Invasions 22(7): 2223–2233. https://doi.org/10.1007/s10530-020-02252-2

MacNeil C, Dick JTA, Alexander ME, Dodd J, Ricciardi A (2013) Predators vs. alien: Differential biotic resistance to an invasive species by two resident predators. NeoBiota 19: 1–19. https://doi.org/10.3897/neobiota.19.4839

Madadi H, Mohajeri Parizi E, Allahyari H, Enkegaard A (2011) Assessment of the biological control capability of *Hippodamia variegata* (Col.: Coccinellidae) using functional response experiments. Journal of Pest Science 84(4): 447–455. https://doi.org/10.1007/s10340-011-0387-9

Marescaux J, Falisse E, Lorquet J, Van Doninck K, Beisel J-N, Descy J-P (2016) Assessing filtration rates of exotic bivalves: Dependence on algae concentration and seasonal factors. Hydrobiologia 777(1): 67–78. https://doi.org/10.1007/s10750-016-2764-0

Matadha D, Hamilton GC, Lashomb JH, Zhang J (2005) Ovipositional preferences and functional response of parasitoids of euonymus scale, *Unaspis euonymi* (Comstock) and San Jose scale, *Quadraspidiotus perniciosus* (Comstock) (Homoptera: Diaspididae). Biological Control 32(3): 337–347. https://doi.org/10.1016/j.biocontrol.2004.12.005

McGlade CLO, Dickey JWE, Kennedy R, Donnelly S, Nelson CA, Dick JTA, Arnott G (2022) Behavioural traits of rainbow trout and brown trout may help explain their differing invasion success and impacts. Scientific Reports 12(1): 1757. https://doi.org/10.1038/s41598-022-05484-5

Médoc V, Spataro T (2015) Predicting the impact of invasive species: A look forward on the comparative functional response approach. Revue d'Écologie 70(1): 114–126. https://doi.org/10.3406/revec.2015.1821 [Terre et Vie]

Médoc V, Albert H, Spataro T (2015) Functional response comparisons among freshwater amphipods: Ratio-dependence and higher predation for *Gammarus pulex* compared to the non-natives *Dikerogammarus villosus* and *Echinogammarus berilloni*. Biological Invasions 17(12): 3625–3637. https://doi.org/10.1007/s10530-015-0984-2

Melbourne BA, Cornell HV, Davies KF, Dugaw CJ, Elmendorf S, Freestone AL, Hall RJ, Harrison S, Hastings A, Holland M, Holyoak M, Lambrinos J, Moore K, Yokomizo H (2007) Invasion in a heterogeneous world: Resistance, coexistence or hostile takeover? Ecology Letters 10(1): 77–94. https://doi.org/10.1111/j.1461-0248.2006.00987.x

Mistri M (2004) Predatory behavior and preference of a successful invader, the mud crab *Dyspanopeus sayi* (Panopeidae), on its bivalve prey. Journal of Experimental Marine Biology and Ecology 312(2): 385–398. https://doi.org/10.1016/j.jembe.2004.07.012

Mofu L, South J, Wasserman RJ, Dalu T, Woodford DJ, Dick JTA, Weyl OLF (2019) Interspecific differences in invader and native fish functional responses illustrate neutral effects on prey but superior invader competitive ability. Freshwater Biology 64(9): 1655–1663. https://doi.org/10.1111/fwb.13361

Mook LJ, Davies DM (1966) The European praying mantis (*Mantis religiosa* L.) as a predator of the red-legged grasshopper (*Melanoplus femurrubrum* (De Geer)). Canadian Entomologist 98(9): 913–918. https://doi.org/10.4039/Ent98913-9

Morrison WE, Hay ME (2011) Feeding and growth of native, invasive and non-invasive alien apple snails (Ampullariidae) in the United States: Invasives eat more and grow more. Biological Invasions 13(4): 945–955. https://doi.org/10.1007/s10530-010-9881-x

Murdoch WW (1969) Switching in general predators: Experiments on predator specificity and stability of prey populations. Ecological Monographs 39(4): 335–354. https://doi.org/10.2307/1942352

Murdoch WW, Oaten A (1975) Predation and population stability. Advances in Ecological Research 9: 1–131. https://doi.org/10.1016/S0065-2504(08)60288-3

Murray GPD, Stillman RA, Britton JR (2016) Habitat complexity and food item size modify the foraging behaviour of a freshwater fish. Hydrobiologia 766(1): 321–332. https://doi.org/10.1007/s10750-015-2465-0

Naranjo SE, Hagler JR (2001) Toward the quantification of predation with predator gut immunoassays: A new approach integrating functional response behavior. Biological Control 20(2): 175–189. https://doi.org/10.1006/bcon.2000.0892

Norbury G, van Overmeire W (2019) Low structural complexity of nonnative grassland habitat exposes prey to higher predation. Ecological Applications 29(2): e01830. https://doi.org/10.1002/eap.1830

Novak M, Stouffer DB (2021) Systematic bias in studies of consumer functional responses. Ecology Letters 24(3): 580–593. https://doi.org/10.1111/ele.13660

Oaten A, Murdoch WW (1975) Functional response and stability in predator-prey systems. American Naturalist 109(967): 289–298. https://doi.org/10.1086/282998

Otturi G, Reggi PE, Battini MÁ, Barriga JP (2020) The effects of trophic interaction between the Patagonian native *Percichthys trucha* and the invasive *Oncorhynchus mykiss* during the juvenile period. Biological Invasions 22(11): 3293–3305. https://doi.org/10.1007/s10530-020-02324-3

Paolucci EM, MacIsaac HJ, Ricciardi A (2013) Origin matters: Alien consumers inflict greater damage on prey populations than do native consumers. Diversity & Distributions 19(8): 988–995. https://doi.org/10.1111/ddi.12073

Papanikolaou NE, Kypraios T, Moffat H, Fantinou A, Perdikis DP, Drovandi C (2021) Predators' Functional Response: Statistical inference, experimental design, and biological interpretation of the handling time. Frontiers in Ecology and Evolution 9: 740848. https://doi.org/10.3389/fevo.2021.740848

Parker IM, Simberloff D, Lonsdale W, Goodell K, Wonham M, Kareiva P, Williamson M, Von Holle B, Moyle P, Byers J, Goldwasser L (1999) Impact: Toward a framework for understanding the ecological effects of invaders. Biological Invasions 1(1): 3–19. https://doi.org/10.1023/A:1010034312781

Paterson RA, Dick JTA, Pritchard DW, Ennis M, Hatcher MJ, Dunn AM (2015) Predicting invasive species impacts: A community module functional response approach reveals context dependencies. Journal of Animal Ecology 84(2): 453–463. https://doi.org/10.1111/1365-2656.12292

Pellan L, Médoc V, Renault D, Spataro T, Piscart C (2016) Feeding choice and predation pressure of two invasive gammarids, *Gammarus tigrinus* and *Dikerogammarus villosus*, under increasing temperature. Hydrobiologia 781(1): 43–54. https://doi.org/10.1007/s10750-015-2312-3

Penk M, Saul WC, Dick JTA, Donohue I, Alexander ME, Linzmaier S, Jeschke JM (2017) A trophic interaction framework for identifying the invasive capacity of novel organisms. Methods in Ecology and Evolution 8(12): 1786–1794. https://doi.org/10.1111/2041-210X.12817

Poley K, Bahlai C, Grieshop M (2018) Functional response of generalist predators to *Halyomorpha halys* (Hemiptera: Pentatomidae) eggs. Environmental Entomology 47(5): 1117–1127. https://doi.org/10.1093/ee/nvy110

Pyšek P, Richardson DM, Pergl J, Jarošík V, Sixtová Z, Weber E (2008) Geographical and taxonomic biases in invasion ecology. Trends in Ecology & Evolution 23(5): 237–244. https://doi.org/10.1016/j.tree.2008.02.002

Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, Carlton JT, Dawson W, Essl F, Foxcroft LC, Genovesi P, Jeschke JM, Kühn I, Liebhold AM, Mandrak NE, Meyerson LA, Pauchard A, Pergl J, Roy HE, Seebens H, van Kleunen M, Vilà M, Wingfield MJ, Richardson DM (2020) Scientists' warning on invasive alien species. Biological Reviews of the Cambridge Philosophical Society 95(6): 1511–1534. https://doi.org/10.1111/brv.12627

R Core Team (2021) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/

Radford IJ (2013) Fluctuating resources, disturbance and plant strategies: Diverse mechanisms underlying plant invasions. Journal of Arid Land 5(3): 284–297. https://doi.org/10.1007/s40333-013-0164-0

Radford IJ, Dickinson KJM, Lord JM (2007) Functional and performance comparisons of invasive *Hieracium lepidulum* and co-occurring species in New Zealand. Austral Ecology 32(3): 338–354. https://doi.org/10.1111/j.1442-9993.2007.01700.x

Ricciardi A, Atkinson SK (2004) Distinctiveness magnifies the impact of biological invaders in aquatic ecosystems. Ecology Letters 7(9): 781–784. https://doi.org/10.1111/j.1461-0248.2004.00642.x

Ricciardi A, Hoopes MF, Marchetti MP, Lockwood JL (2013) Progress toward understanding the ecological impacts of nonnative species. Ecological Monographs 83(3): 263–282. https://doi.org/10.1890/13-0183.1

Ricciardi A, Iacarella JC, Aldridge DC, Blackburn TM, Carlton JT, Catford JA, Dick JTA, Hulme PE, Jeschke JM, Liebhold AM, Lockwood JL, MacIsaac HJ, Meyerson LA, Pyšek P, Richardson DM, Ruiz GM, Simberloff D, Vilà M, Wardle DA (2021) Four priority areas to advance invasion science in the face of rapid environmental change. Environmental Reviews 29(2): 119–141. https://doi.org/10.1139/er-2020-0088

Richardson DM, Ricciardi A (2013) Misleading criticisms of invasion science: A field guide. Diversity & Distributions 19(12): 1461–1467. https://doi.org/10.1111/ddi.12150

Robertson PA, Mill A, Novoa A, Jeschke JM, Essl F, Gallardo B, Geist J, Jarić I, Lambin X, Musseau C, Pergl J, Pyšek P, Rabitsch W, von Schmalensee M, Shirley M, Strayer DL, Stefansson RA, Smith K, Booy O (2020) A proposed unified framework to describe the management of biological invasions. Biological Invasions 22(9): 2633–2645. https://doi.org/10.1007/s10530-020-02298-2

Rosenbaum B, Rall BC (2018) Fitting functional responses: Direct parameter estimation by simulating differential equations. Methods in Ecology and Evolution 9(10): 2076–2090. https://doi.org/10.1111/2041-210X.13039

Rossiter-Rachor NA, Setterfield SA, Douglas MM, Hutley LB, Cook GD, Schmidt S (2009) Invasive *Andropogon gayanus* (gamba grass) is an ecosystem transformer of nitrogen re-

lations in Australian savanna. Ecological Applications 19(6): 1546–1560. https://doi.org/10.1890/08-0265.1

Salo P, Korpimäki E, Banks PB, Nordström M, Dickman CR (2007) Alien predators are more dangerous than native predators to prey populations. Proceedings of the Royal Society B, Biological Sciences 274(1615): 1237–1243. https://doi.org/10.1098/rspb.2006.0444

Saul WC, Jeschke J (2015) Eco-evolutionary experience in novel species interactions. Ecology Letters 18(3): 236–245. https://doi.org/10.1111/ele.12408

Savino V, Coviella CE, Luna MG (2012) Reproductive biology and functional response of *Dineulophus phtorimaeae*, a natural enemy of the tomato moth, *Tuta absoluta*. Journal of Insect Science 12(153): 153. https://doi.org/10.1673/031.012.15301

Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, Dullinger S, Genovesi P, Hulme PE, van Kleunen M, Kühn I, Jeschke JM, Lenzner B, Liebhold AM, Pattison Z, Pergl J, Pyšek P, Winter M, Essl F (2021) Projecting the continental accumulation of alien species through to 2050. Global Change Biology 27(5): 970–982. https://doi.org/10.1111/gcb.15333

Simberloff D (2006a) Invasional meltdown 6 years later: Important phenomenon, unfortunate metaphor, or both? Ecology Letters 9(8): 912–919. https://doi.org/10.1111/j.1461-0248.2006.00939.x

Simberloff D (2006b) Risk assessments, blacklists, and white lists for introduced species: Are predictions good enough to be useful? Agricultural and Resource Economics Review 35(1): 1–10. https://doi.org/10.1017/S1068280500010005

Simberloff D, Vitule JRS (2014) A call for an end to calls for the end of invasion biology. Oikos 123(4): 408–413. https://doi.org/10.1111/j.1600-0706.2013.01228.x

Simberloff D, Von Holle B (1999) Positive interactions of nonindigenous species: Invasional meltdown? Biological Invasions 1(1): 21–32. https://doi.org/10.1023/A:1010086329619

Simberloff D, Souza L, Nũnez MA, Barrios-Garcia MN, Bunn W (2012) The natives are restless, but not often and mostly when disturbed. Ecology 93(3): 598–607. https://doi.org/10.1890/11-1232.1

Sinclair ARE, Olsen PD, Redhead TD (1990) Can predators regulate small mammal populations? Evidence from house mouse outbreaks in Australia. Oikos 59(3): 382–392. https://doi.org/10.2307/3545150

Sinclair ARE, Pech RP, Dickman CR, Hik D, Mahon P, Newsome AE (1998) Predicting effects of predation on conservation of endangered prey. Conservation Biology 12(3): 564–575. https://doi.org/10.1046/j.1523-1739.1998.97030.x

Smout S, Asseburg C, Matthiopoulos J, Fernández C, Redpath S, Thirgood S, Harwood J (2010) The functional response of a generalist predator. PLoS ONE 5(5): e10761. https://doi.org/10.1371/journal.pone.0010761

Smout S, Rindorf A, Wanless S, Daunt F, Harris MP, Matthiopoulos J (2013) Seabirds maintain offspring provisioning rate despite fluctuations in prey abundance: A multi-species functional response for guillemots in the North Sea. Journal of Applied Ecology 50(4): 1071–1079. https://doi.org/10.1111/1365-2664.12095

Solomon ME (1949) The natural control of animal populations. Journal of Animal Ecology 18(1): 1–35. https://doi.org/10.2307/1578

Sorte CJB, Ibáñez I, Blumenthal DM, Molinari NA, Miller LP, Grosholz ED, Diez JM, D'Antonio CM, Olden JD, Jones SJ, Dukes JS (2013) Poised to prosper? A cross-system comparison of climate change effects on native and non-native species performance. Ecology Letters 16(2): 261–270. https://doi.org/10.1111/ele.12017

South J, Dick JTA, McCard M, Barrios-O'Neill D, Anton A (2017) Predicting predatory impact of juvenile invasive lionfish (*Pterois volitans*) on a crustacean prey using functional response analysis: Effects of temperature, habitat complexity and light regimes. Environmental Biology of Fishes 100(10): 1155–1165. https://doi.org/10.1007/s10641-017-0633-y

South J, McCard M, Khosa D, Mofu L, Madzivanzira TC, Dick JTA, Weyl OLF (2019) The effect of prey identity and substrate type on the functional response of a globally invasive crayfish. NeoBiota 52: 9–24. https://doi.org/10.3897/neobiota.52.39245

Strayer DL (2010) Alien species in fresh waters: Ecological effects, interactions with other stressors, and prospects for the future. Freshwater Biology 55: 152–174. https://doi.org/10.1111/j.1365-2427.2009.02380.x

Swanepoel LH, Somers MJ, Dalerum F (2015) Functional responses of retaliatory killing versus recreational sport hunting of leopards in South Africa. PLoS ONE 10(4): 1–11. https://doi.org/10.1371/journal.pone.0125539

Taylor NG, Dunn AM (2018) Predatory impacts of alien decapod Crustacea are predicted by functional responses and explained by differences in metabolic rate. Biological Invasions 20(10): 2821–2837. https://doi.org/10.1007/s10530-018-1735-y

Tilman D (1977) Resource competition between plankton algae: An experimental and theoretical approach. Ecology 58(2): 338–348. https://doi.org/10.2307/1935608

Tilves U, Purcell JE, Marambio M, Canepa A, Olariaga A, Fuentes V (2013) Predation by the scyphozoan *Pelagia noctiluca* on *Mnemiopsis leidyi* ctenophores in the NW Mediterranean Sea. Journal of Plankton Research 35(1): 218–224. https://doi.org/10.1093/plankt/fbs082

Toscano BJ, Griffen BD (2013) Predator size interacts with habitat structure to determine the allometric scaling of the functional response. Oikos 122(3): 454–462. https://doi.org/10.1111/j.1600-0706.2012.20690.x

Toscano BJ, Newsome B, Griffen BD (2014) Parasite modification of predator functional response. Oecologia 175(1): 345–352. https://doi.org/10.1007/s00442-014-2905-y

Twardochleb LA, Novak M, Moore JW (2012) Using the functional response of a consumer to predict biotic resistance to invasive prey. Ecological Applications 22(4): 1162–1171. https://doi.org/10.1890/11-0871.1

Uiterwaal SF, DeLong JP (2020) Functional responses are maximized at intermediate temperatures. Ecology 101(4): 1–10. https://doi.org/10.1002/ecy.2975

Uiterwaal SF, Dell AI, Delong JP (2019) Arena size modulates functional responses via behavioral mechanisms. Behavioral Ecology 30(2): 483–489. https://doi.org/10.1093/beheco/ary188

Uiterwaal SF, Lagerstrom IT, Lyon SR, DeLong JP (2022) FoRAGE database: A compilation of functional responses for consumers and parasitoids. Ecology 103(7): e3706. https://doi.org/10.1002/ecy.3706

Uszko W, Diehl S, Wickman J (2020) Fitting functional response surfaces to data: A best practice guide. Ecosphere 11(4): e03051. https://doi.org/10.1002/ecs2.3051

Valéry L, Fritz H, Lefeuvre JCC, Simberloff D (2008) In search of a real definition of the biological invasion phenomenon itself. Biological Invasions 10(8): 1345–1351. https://doi.org/10.1007/s10530-007-9209-7

van Driesche RG, Bellows TS (1996) Biological Control. Springer US, Boston, MA, 539 pp. https://doi.org/10.1007/978-1-4613-1157-7

Vonesh J, McCoy M, Altwegg R, Landi P, Measey J (2017) Functional responses can't unify invasion ecology. Biological Invasions 19(5): 1673–1676. https://doi.org/10.1007/s10530-016-1356-2

Vucic-Pestic O, Rall BC, Kalinkat G, Brose U (2010) Allometric functional response model: Body masses constrain interaction strengths. Journal of Animal Ecology 79(1): 249–256. https://doi.org/10.1111/j.1365-2656.2009.01622.x

Wang X, Biondi A, Daane KM (2020) Functional responses of three candidate asian larval parasitoids evaluated for classical biological control of *Drosophila suzukii* (Diptera: Drosophilidae). Journal of Economic Entomology 113(1): 73–80. https://doi.org/10.1093/jee/toz265

Werner EE, Gilliam JF (1984) The ontogenetic niche and species interactions in size-structured populations. Annual Review of Ecology and Systematics 15(1): 393–425. https://doi.org/10.1146/annurev.es.15.110184.002141

Xu M, Mu X, Dick JTA, Fang M, Gu D, Luo D, Zhang J, Luo J, Hu Y (2016) Comparative functional responses predict the invasiveness and ecological impacts of alien herbivorous snails. PLoS ONE 11(1): e0147017. https://doi.org/10.1371/journal.pone.0147017

Yodzis P (1994) Predator-prey theory and management of multispecies fisheries. Ecological Applications 4(1): 51–58. https://doi.org/10.2307/1942114

## Supplementary material 1

**Flow chart**

Authors: Larissa Faria, Ross N. Cuthbert, James W. E. Dickey, Jonathan M. Jeschke, Anthony Ricciardi, Jaimie T. A. Dick, Jean R. S. Vitule

Data type: figure (.docx file)

Explanation note: Flow chart showing the steps followed to evaluate studies that used the Functional Response (FR) related to non-native species (NNS) included in the systematic review.

Copyright notice: This dataset is made available under the Open Database License (http://opendatacommons.org/licenses/odbl/1.0/). The Open Database License (ODbL) is a license agreement intended to allow users to freely share, modify, and use this Dataset while maintaining this same freedom for others, provided that the original source and author(s) are credited.

Link: https://doi.org/10.3897/neobiota.85.98902.suppl1

## Supplementary material 2

**List of the data extracted from publications included in the systematic review**

Authors: Larissa Faria, Ross N. Cuthbert, James W. E. Dickey, Jonathan M. Jeschke, Anthony Ricciardi, Jaimie T. A. Dick, Jean R. S. Vitule

Data type: table (.docx file)

Copyright notice: This dataset is made available under the Open Database License (http://opendatacommons.org/licenses/odbl/1.0/). The Open Database License (ODbL) is a license agreement intended to allow users to freely share, modify, and use this Dataset while maintaining this same freedom for others, provided that the original source and author(s) are credited.

Link: https://doi.org/10.3897/neobiota.85.98902.suppl2

## Supplementary material 3

**Journal trends analysis**

Authors: Larissa Faria, Ross N. Cuthbert, James W. E. Dickey, Jonathan M. Jeschke, Anthony Ricciardi, Jaimie T. A. Dick, Jean R. S. Vitule

Data type: figure (.docx file)

Copyright notice: This dataset is made available under the Open Database License (http://opendatacommons.org/licenses/odbl/1.0/). The Open Database License (ODbL) is a license agreement intended to allow users to freely share, modify, and use this Dataset while maintaining this same freedom for others, provided that the original source and author(s) are credited.

Link: https://doi.org/10.3897/neobiota.85.98902.suppl3

## Supplementary material 4

**List of treatments used by the studies deriving Functional Response (FR) curves under different biotic and abiotic contexts**

Authors: Larissa Faria, Ross N. Cuthbert, James W. E. Dickey, Jonathan M. Jeschke, Anthony Ricciardi, Jaimie T. A. Dick, Jean R. S. Vitule

Data type: table (.docx file)

Copyright notice: This dataset is made available under the Open Database License (http://opendatacommons.org/licenses/odbl/1.0/). The Open Database License (ODbL) is a license agreement intended to allow users to freely share, modify, and use this Dataset while maintaining this same freedom for others, provided that the original source and author(s) are credited.

Link: https://doi.org/10.3897/neobiota.85.98902.suppl4

## Supplementary material 5

**List of publications included in the systematic review**

Authors: Larissa Faria, Ross N. Cuthbert, James W. E. Dickey, Jonathan M. Jeschke, Anthony Ricciardi, Jaimie T. A. Dick, Jean R. S. Vitule

Data type: (.docx file)

Copyright notice: This dataset is made available under the Open Database License (http://opendatacommons.org/licenses/odbl/1.0/). The Open Database License (ODbL) is a license agreement intended to allow users to freely share, modify, and use this Dataset while maintaining this same freedom for others, provided that the original source and author(s) are credited.

Link: https://doi.org/10.3897/neobiota.85.98902.suppl5